An Intro to Ion Traps and the Berkeley ElectroStatic Trap

Outline

- Short intro to ion traps.
- A novel ElectroStatic trap.
- Some possible applications.
- Project status.

Why Ion Traps?

- Localization.
- Low Energy.
- Dilute System.

Can be used for...

- Quantum Information Measurements.
- Mass Measurements.
- Beyond SM high precision studies (EDM, β decay, APV,....).

General Principles

- 3D trapping requires a potential minimum. Conveniently taken to be harmonic.

$$F \propto -\vec{r}$$

$$F = -\nabla U$$

$$\Phi = \frac{\Phi_0}{d^2}(Ax^2 + Bx^2 + Cz^2)$$

- In general Φ can be a time-dependent function.
- Also note that this means no electrostatic traps.

$$\nabla^2 \Phi = 0 \Rightarrow A + B + C = 0$$

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Only saddles in 3D.
"Ernshaw's Theorem"
(more on this later)

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General Principles

$$\nabla^2\Phi = 0 \Rightarrow A + B + C = 0$$

Take rotational symmetry to get A=B=1, C=-2.

$$\Phi = \frac{\phi_0}{d^2}(x^2 + y^2 - 2z^2) = \frac{\phi_0}{d^2}(\rho^2 - 2z^2)$$

Hyperbolic electrode surfaces:

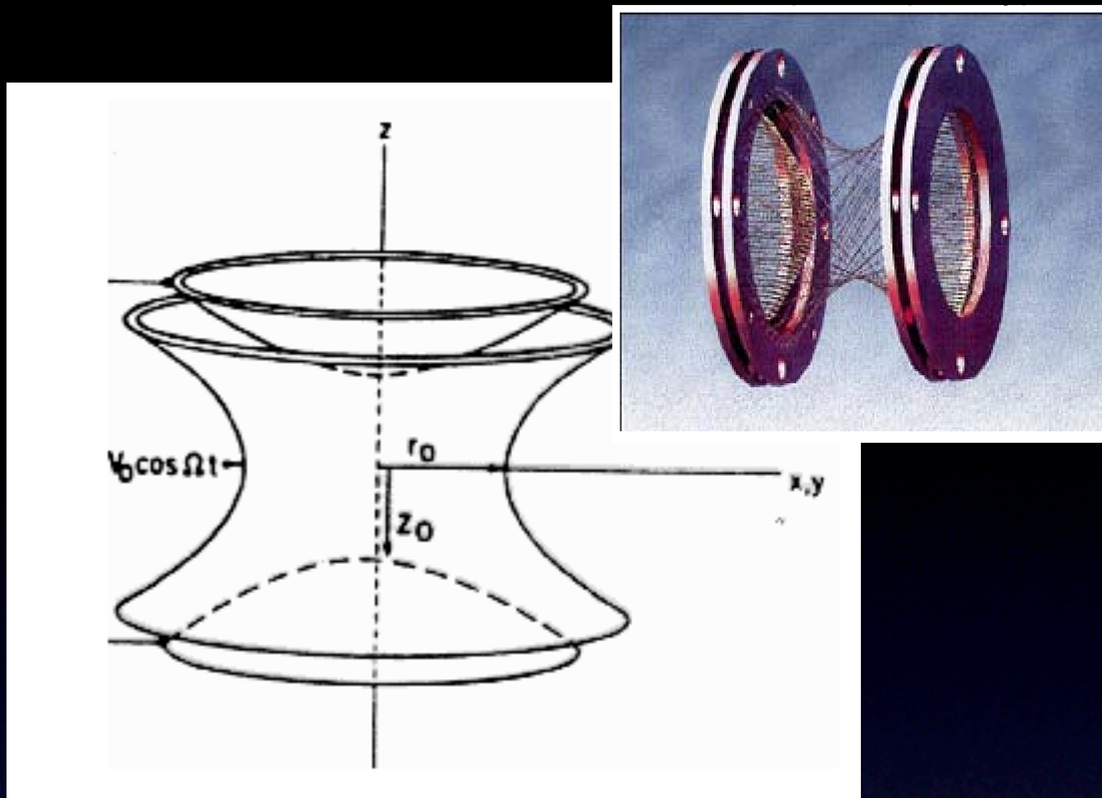
$$\rho^2 - 2z^2 = r_0^2$$

$$\rho^2 - 2z^2 = -2z_0^2$$

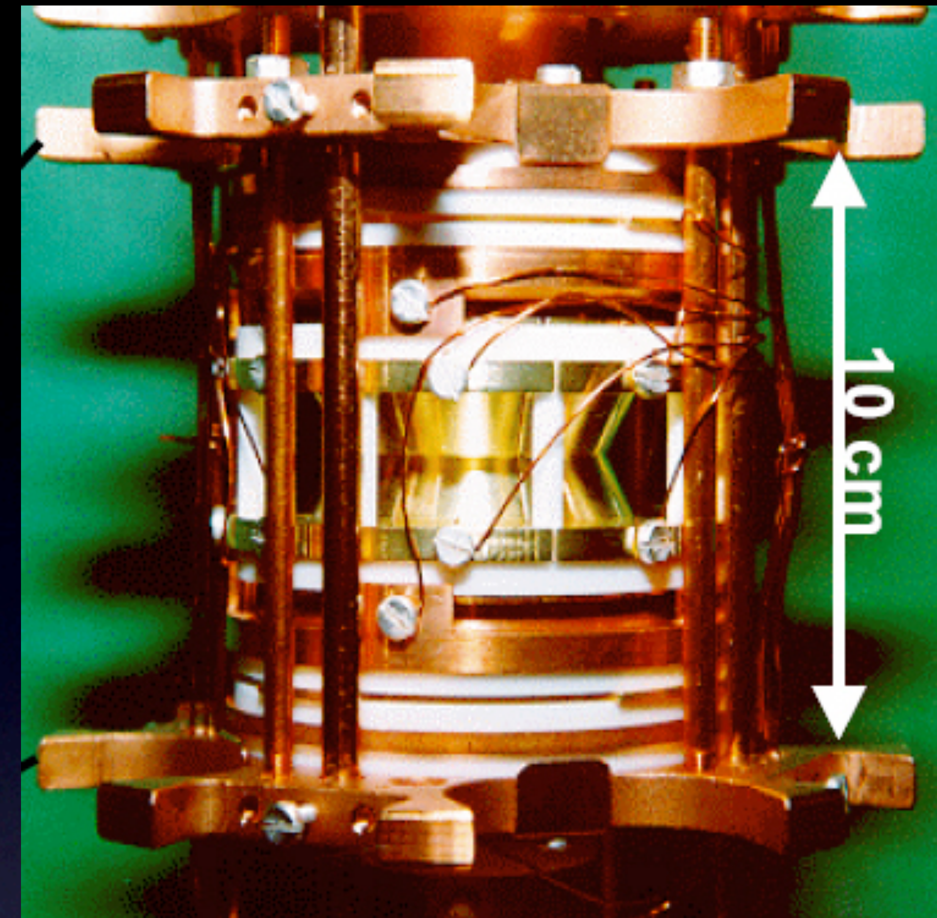
$$d^2 = r_0^2 + 2z_0^2$$

Two general types of traps:

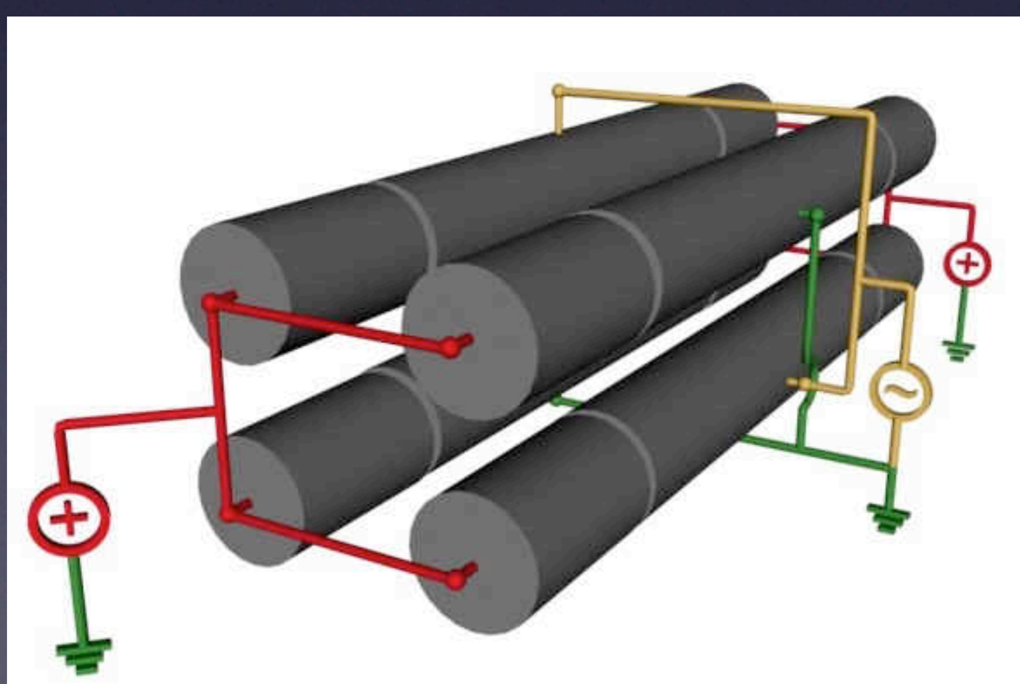
- Penning trap: superimpose a magnetic field along the z axis.
- Paul trap: use time varying (RF) electric fields.
- Linear variant of the Paul trap.



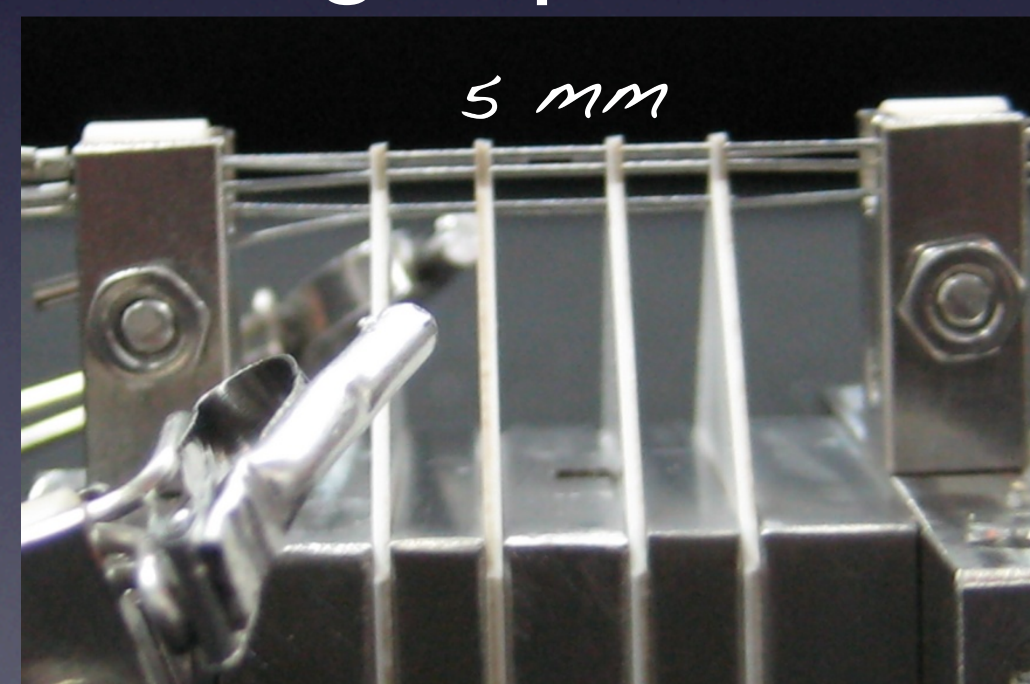
RF Paul Trap



Penning trap at ISOLDE



Linear Paul Trap



Linear Paul Trap at WI

Some Math (sorry...)

Paul Traps

$$\Phi = \frac{U_0 + V_0 \cos \Omega t}{2d^2}(r^2 - 2z^2)$$

Applied between ring and endcaps

EOM (homogeneous Mathieu):

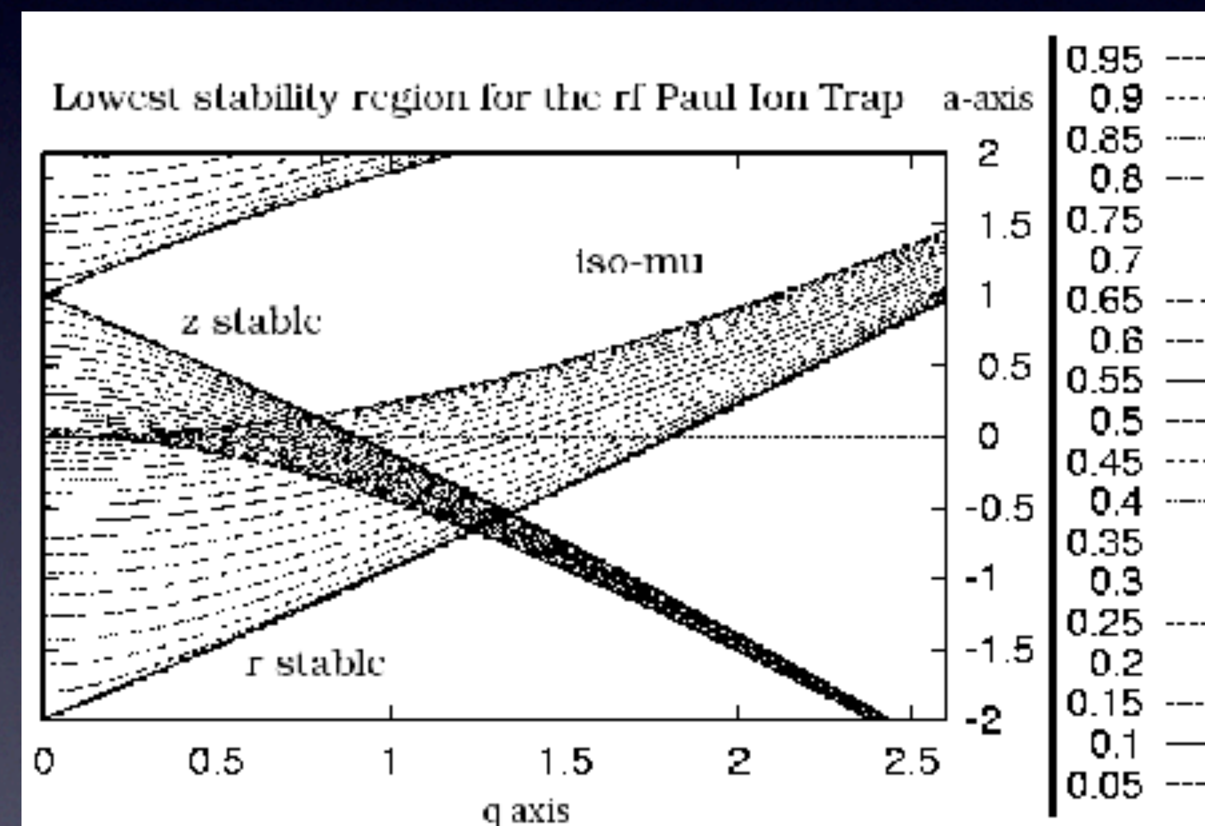
$$\frac{\partial^2 u}{\partial t^2} = \frac{Q}{Md^2}(U_0 + V_0 \cos \Omega t)u$$

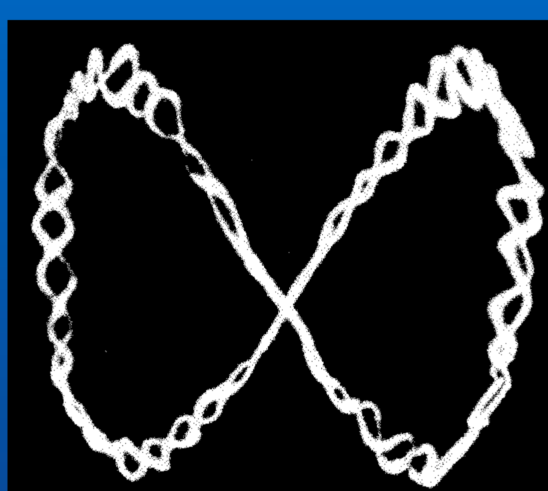
$$\frac{\partial^2 u}{\partial t^2} + (a - 2q\tau)u = 0$$

$$(\tau = \Omega t,\ a_x = a_y = -2a_z = -4QU_0/Md^2\Omega^2,$$

$$q_z = q_y = 2q_z = 2QV_0/Md^2\Omega^2)$$

Stability Diagram





Slow *macro*motion super imposed with RF drive frequency

Wuerker et al., J. Appl Phys 30, 342 (1959)

$$u_i(t) \simeq A\left(1 - \frac{q_i}{2}\cos \Omega t\right) cos\omega_i t$$

$$\omega_i = \beta_i \Omega/2,\ \beta_i \simeq a_i + q_i^2/2$$

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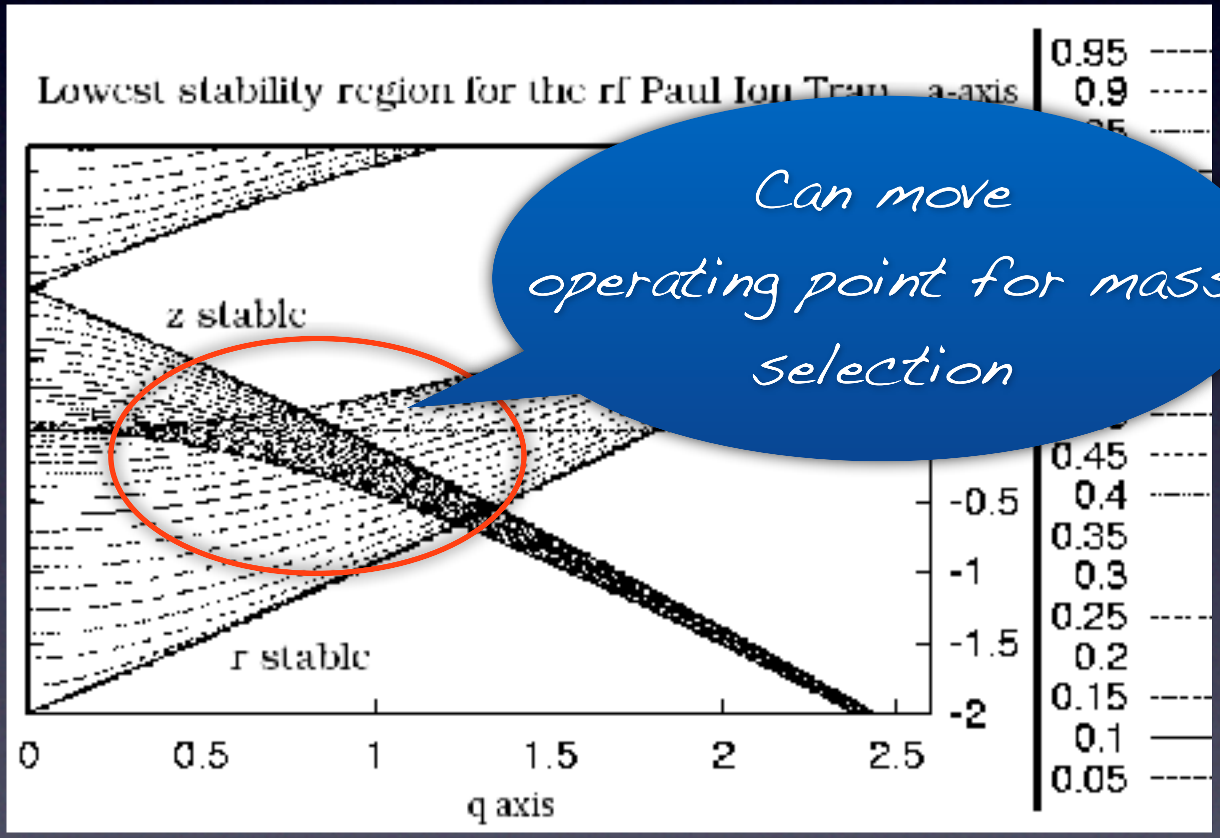

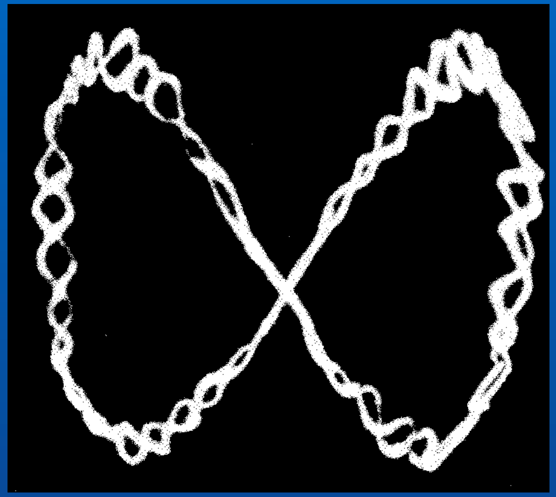

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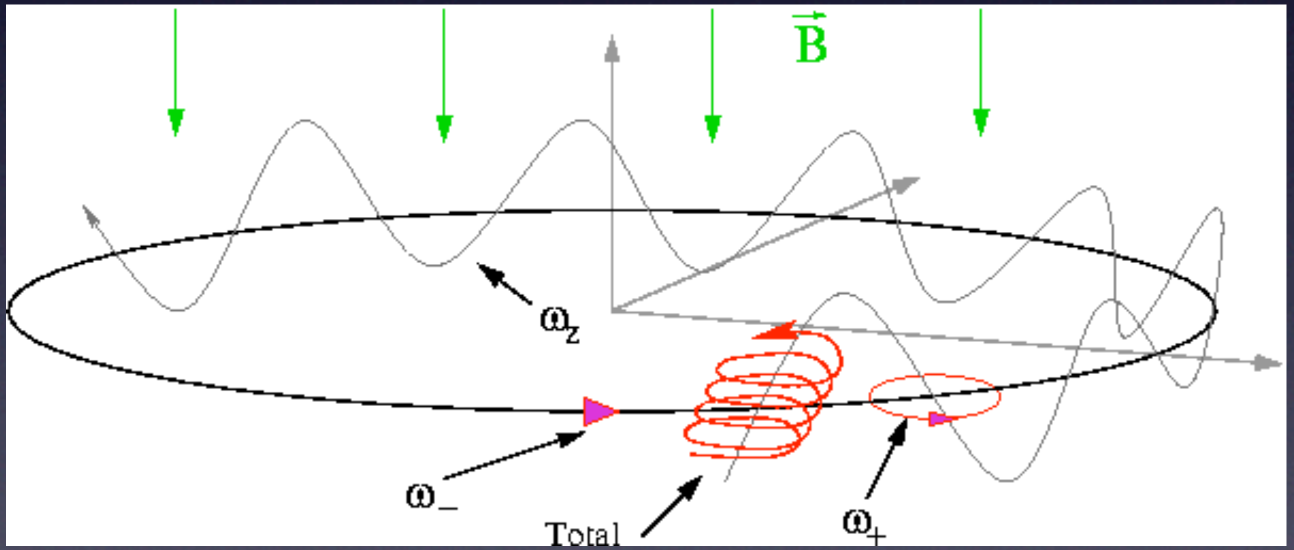
Penning Traps

$$\Phi = \frac{\Phi_o}{2d^2}(r^2 - 2z^2)$$
$$\vec{B} = (0, 0, B)$$
$$\vec{F} = -Q\Phi + Q(\vec{v} \times \vec{B})$$

Apply a magnetic field + DC electric field

$$\frac{d^2x}{dt^2} - w_c^2\frac{dy}{dt} - \frac{1}{2}w_z^2 x = 0$$
$$\frac{d^2y}{dt^2} + w_c^2\frac{dx}{dt} - \frac{1}{2}w_z^2 x = 0$$
$$\frac{d^2z}{dt^2} + w_z^2 z = 0$$
$$w_z = \sqrt{\frac{2Q\Phi_0}{Md^2}},\ w_c = \frac{|QB_0|}{M}$$



$$w_+ = \frac{1}{2}(w_c + \sqrt{w_c^2 - 2w_z^2})$$
$$w_- = \frac{1}{2}(w_c - \sqrt{w_c^2 - 2w_z^2})$$

Now What?
Detection

- Destructive:
    - Lower endcap voltage.
    - HV kick.
    - TOF-ICR (Penning Trap).

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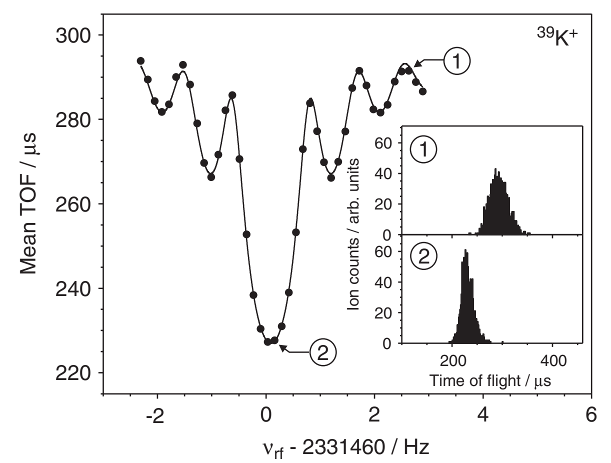
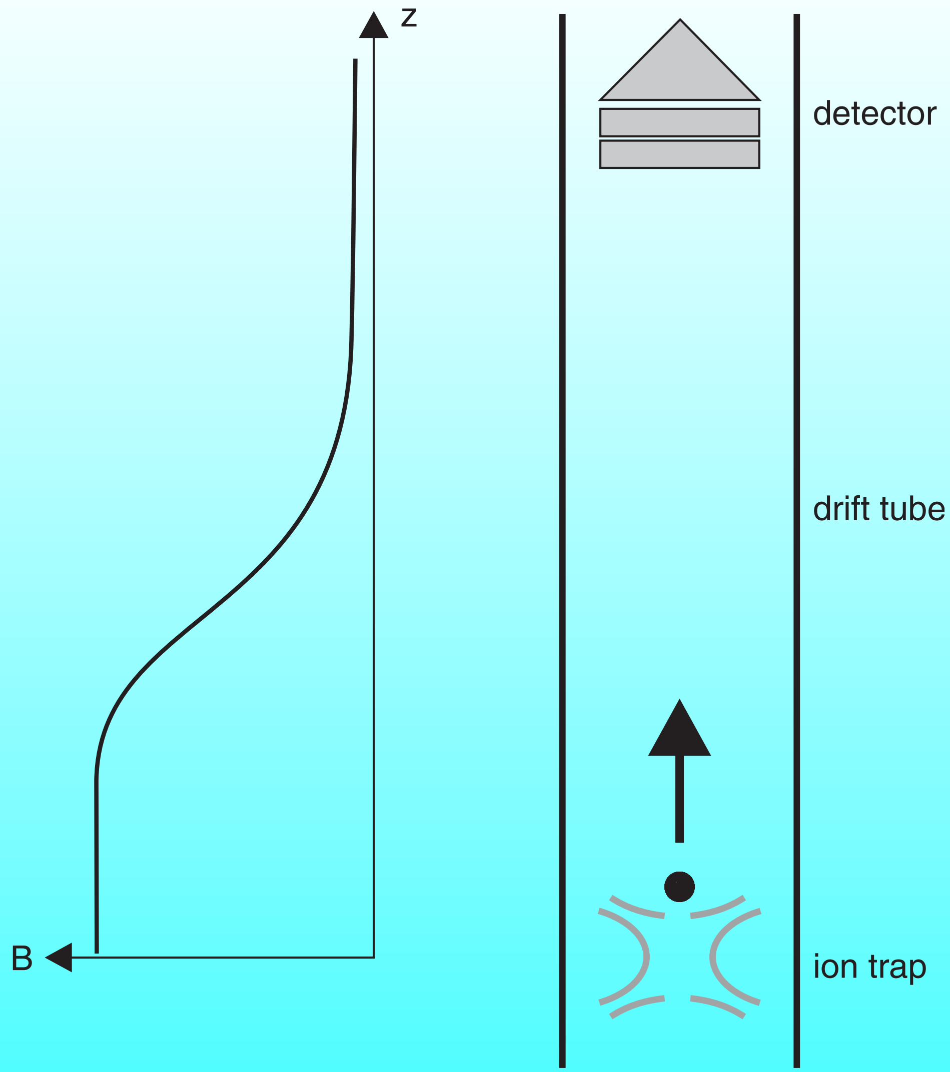


Resolution of ~10^{-9} achieved for stable ions.

K. Blaum, Phys. Rep. 425, 1 (2006)



$$\vec{F} = -\vec{\mu}(\nabla\vec{B}) = -\frac{E_r}{B}\frac{\partial B}{\partial z}\hat{z}$$

$$T_{tof} = \int_0^{z_1}\sqrt{\frac{M}{2(E_0 - qU(z) - \mu B(z))}}$$

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- Non-Destructive:

Now What?

Detection

- Destructive:
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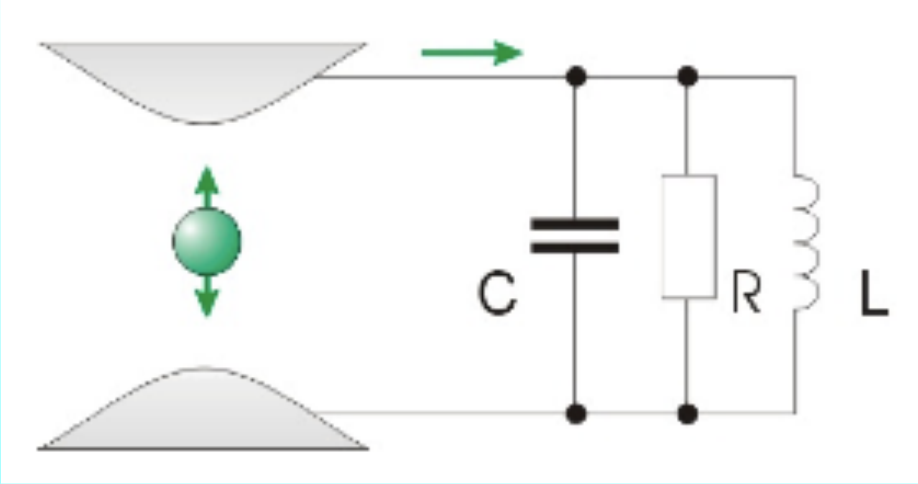
- Non-Destructive:
  - Bolometric detection.

Moving ion = Moving charge = current



$$I = \Gamma \frac{q\dot{z}}{2z_0}$$

$$U_{noise} = \sqrt{4k_B T R \Delta\nu}$$

Also cools ions

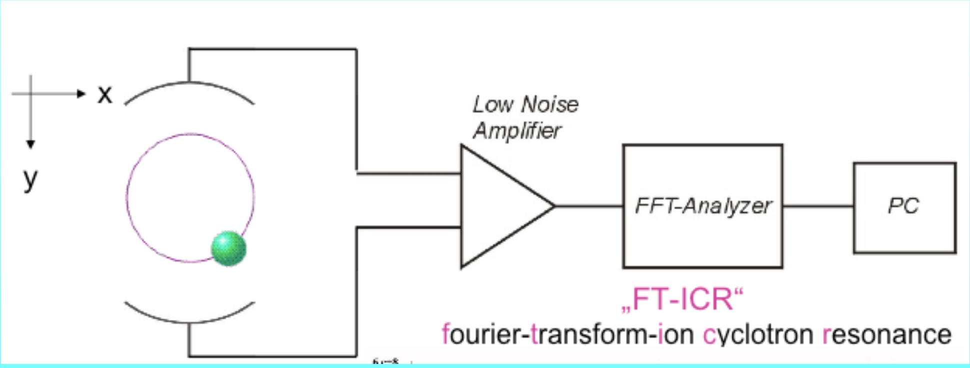
(resistive cooling)

Now What?
Detection

- Destructive:
  - Lower endcap voltage.
  - HV kick.
  - TOF-ICR (Penning Trap).
- Non-Destructive:
  - Bolometric detection.
  - Fourier Transform.
    - Broadband.
    - Resonant.

Moving ion = Moving charge = current

Detection of image charges on electrodes

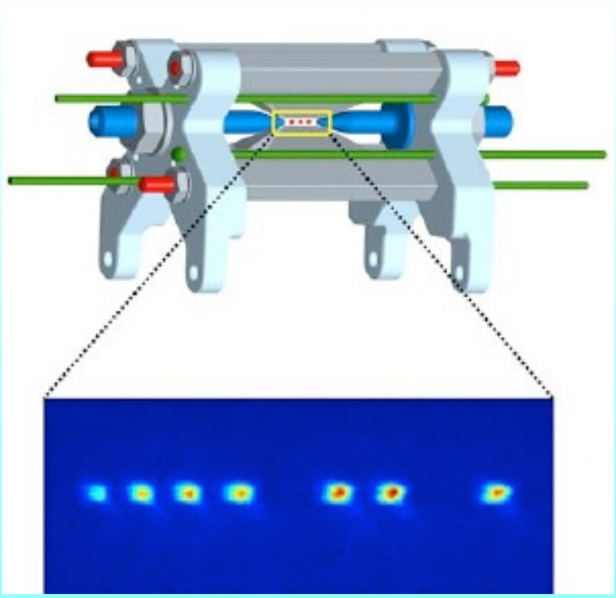


More on this later

Now What?
Detection

- Destructive:
  - Lower endcap voltage.
  - HV kick.
  - TOF-ICR (Penning Trap).
- Non-Destructive:
  - Bolometric detection.
  - Fourier Transform.
    - Broadband.
    - Resonant.
  - Optical.

Moving ion = Moving charge = current



Easy, intuitive, cooool, but:

- Expensive.
- Limited (mostly alkali-like ions).

Also, lets you do laser cooling.

An Electrostatic Ion Beam Trap (EIBT) and (*some*) Possible Applications

Ernshaw's Theorem

A collection of point charges cannot be maintained in a stable stationary equilibrium configuration solely by the electrostatic interaction of the charges.

Restatement of Gauss' Law (for free space)

$$\boxed{\nabla \cdot E \propto \nabla \cdot F = -\nabla^2 \phi = 0}$$

No local minima or maxima in free space (only saddle points).

Naively speaking → No electrostatic ion traps

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Exceptions for:

Time varying & Magnetic fields.

Electronic correction.

Diamagnetic materials (aka "Floating Frog").

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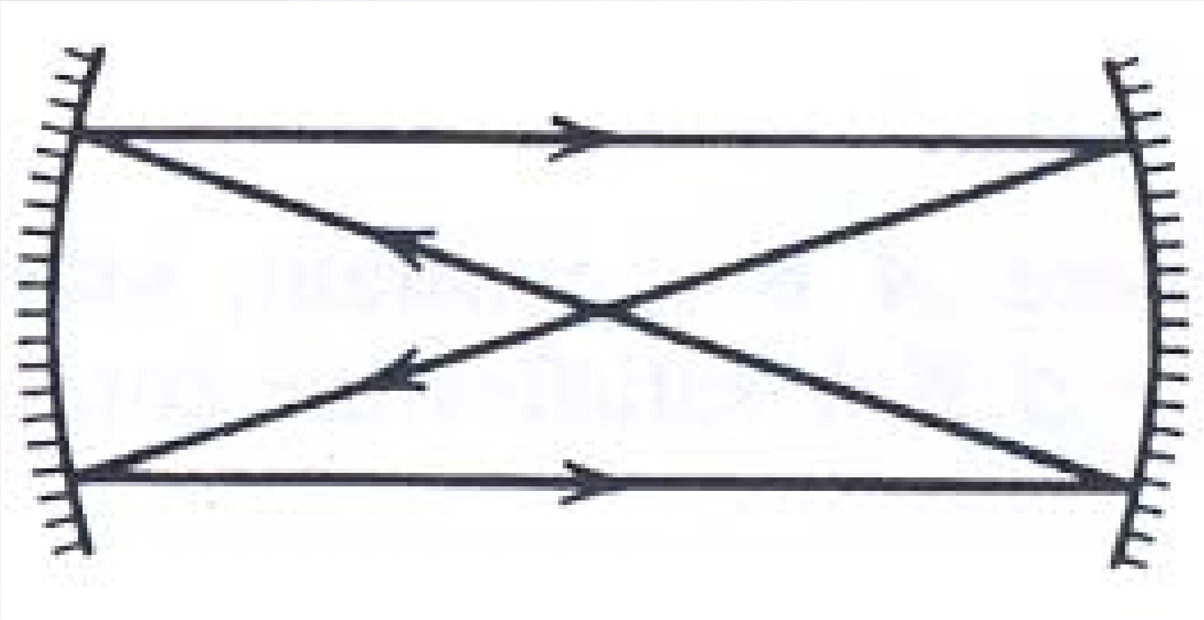
An Electrostatic Ion Beam Trap (EIBT) and (*some*) Possible Applications

But what about moving ions...

Ernshaw's theorem talks about stationary charges.
Moving charges in an electrostatic field actually "see" changing fields.
Trap design very similar to a resonant cavity for laser light.



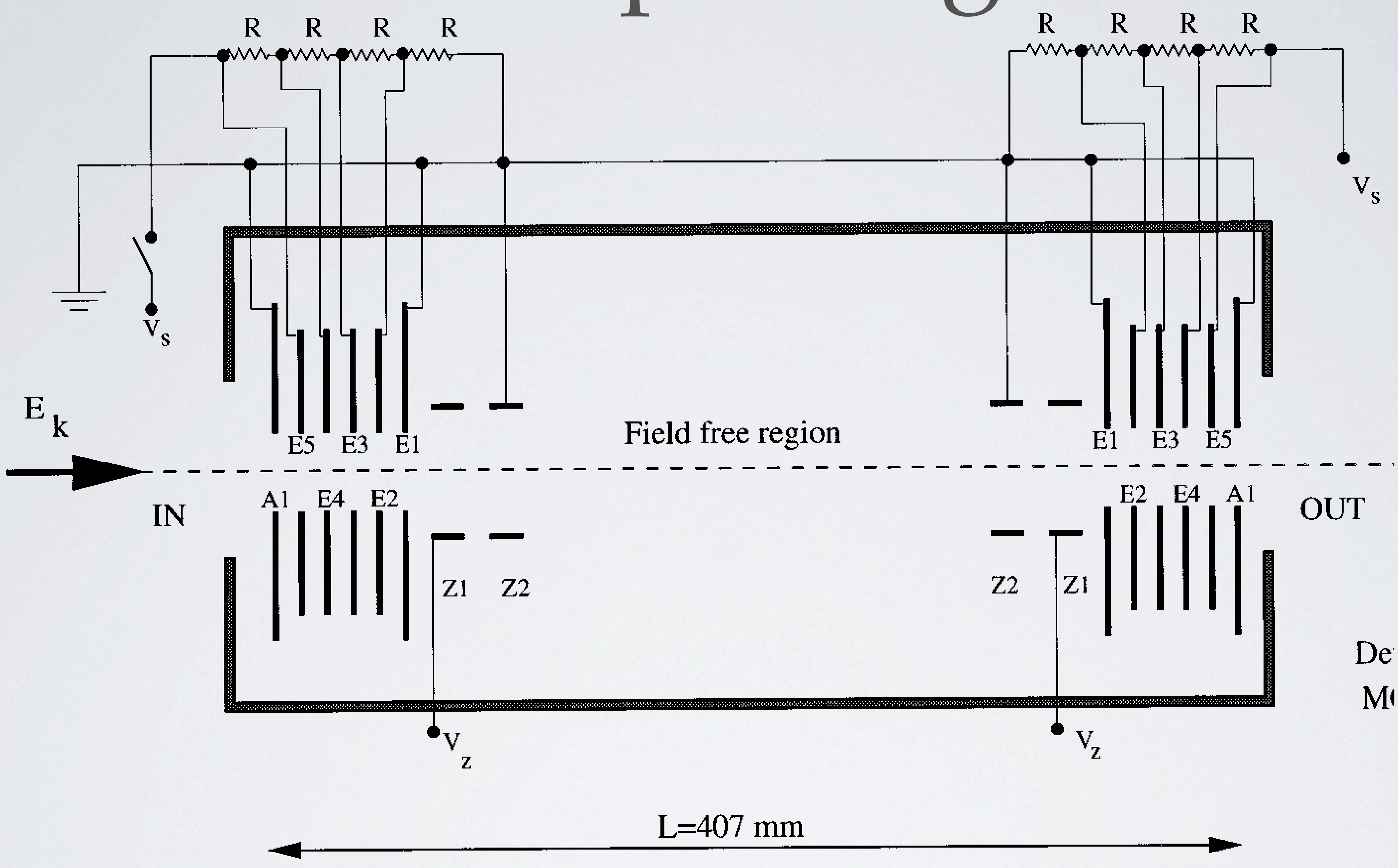
Optical Stability Condition

$$\frac{L}{4} \leq f \leq \infty$$

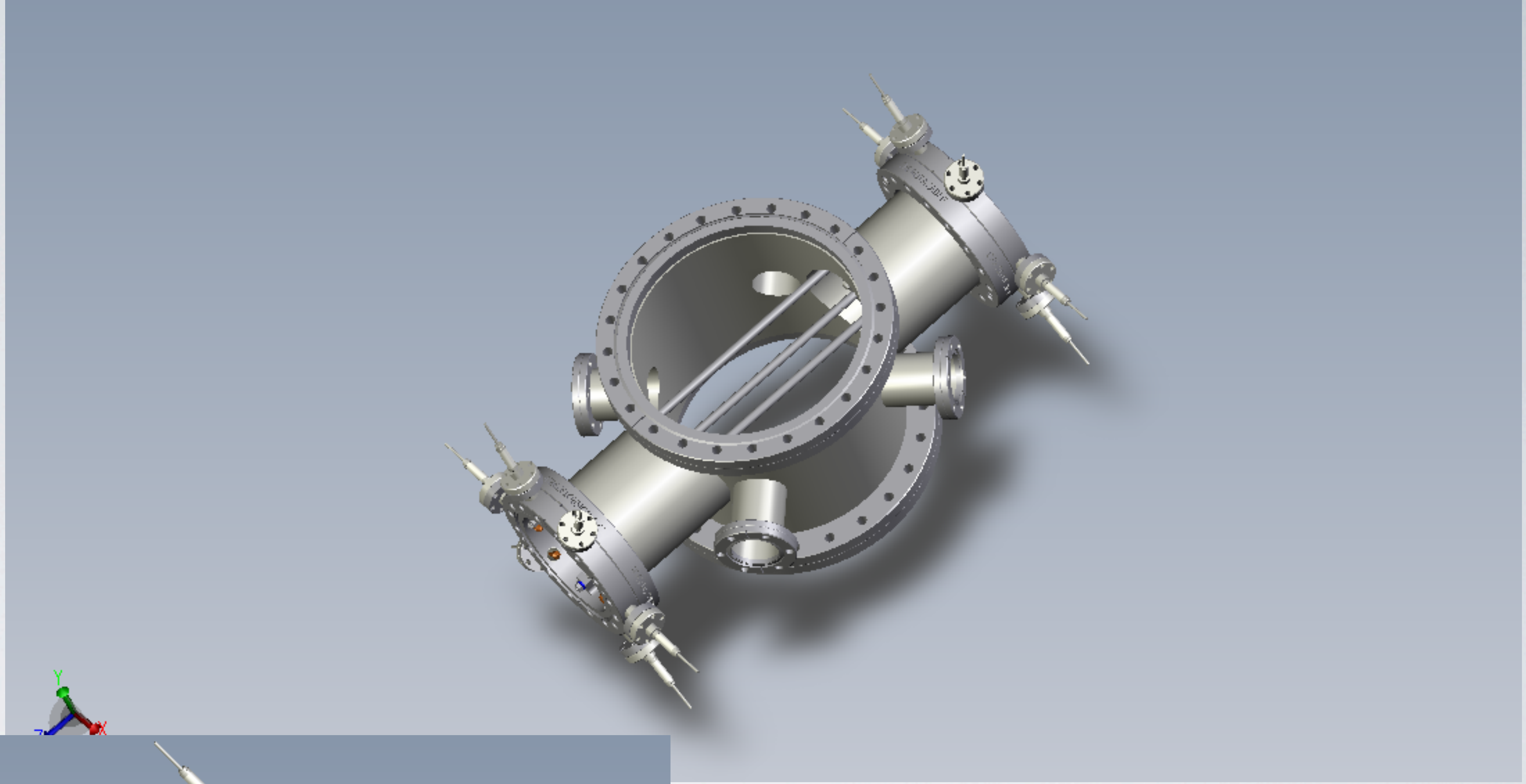
Confining Potential Maximum

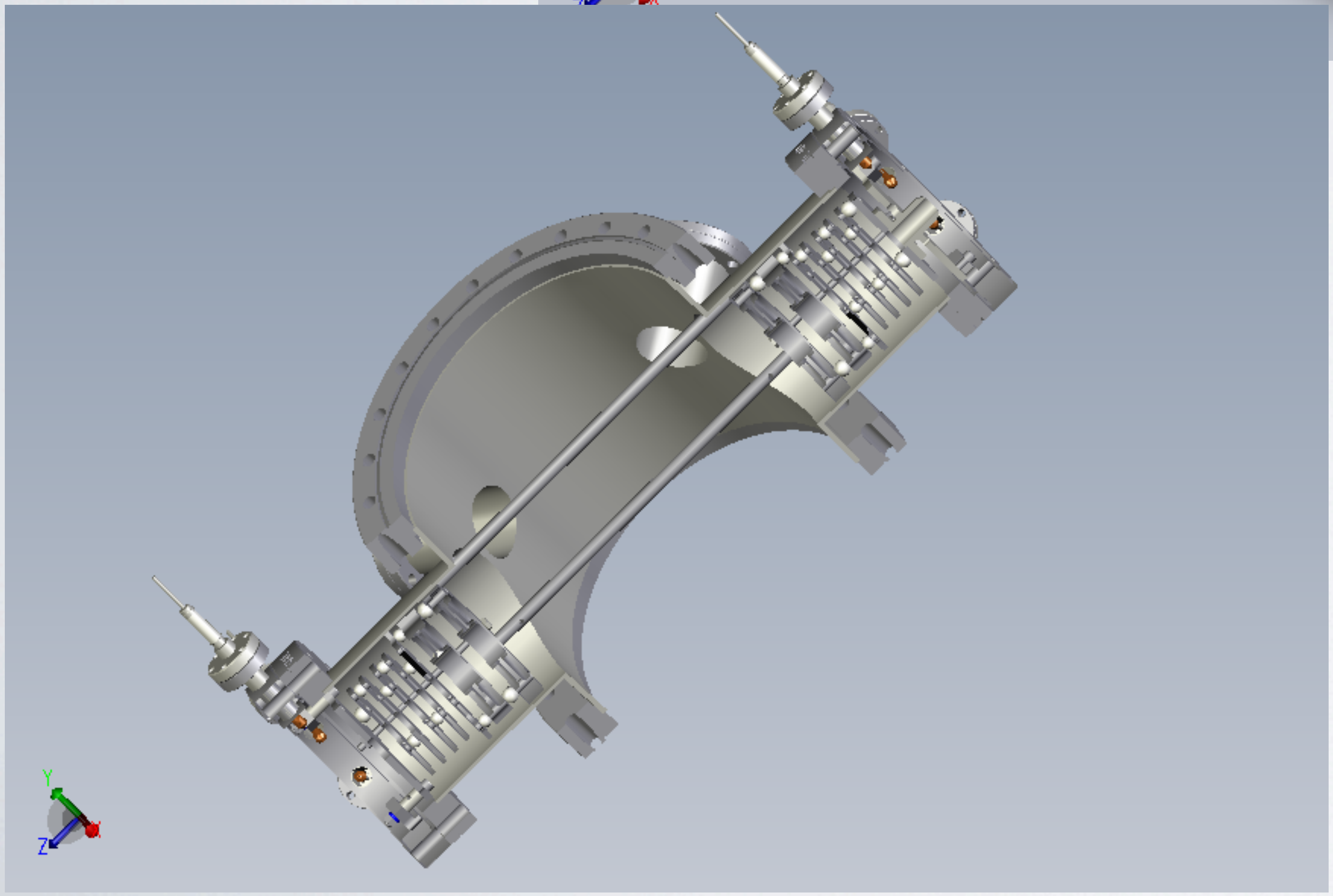
$$q\,e\,V_s > E_k$$

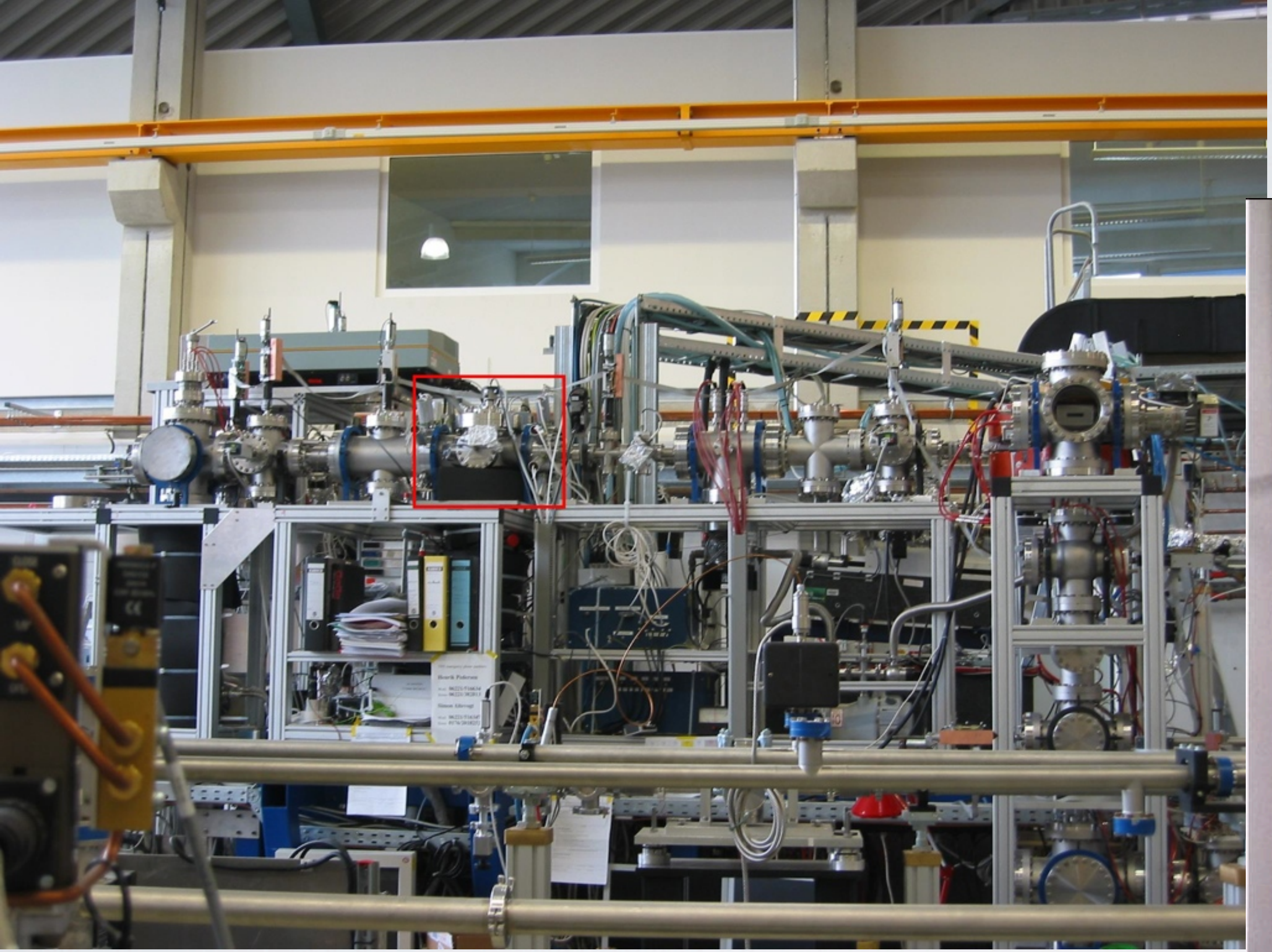
Trap Design

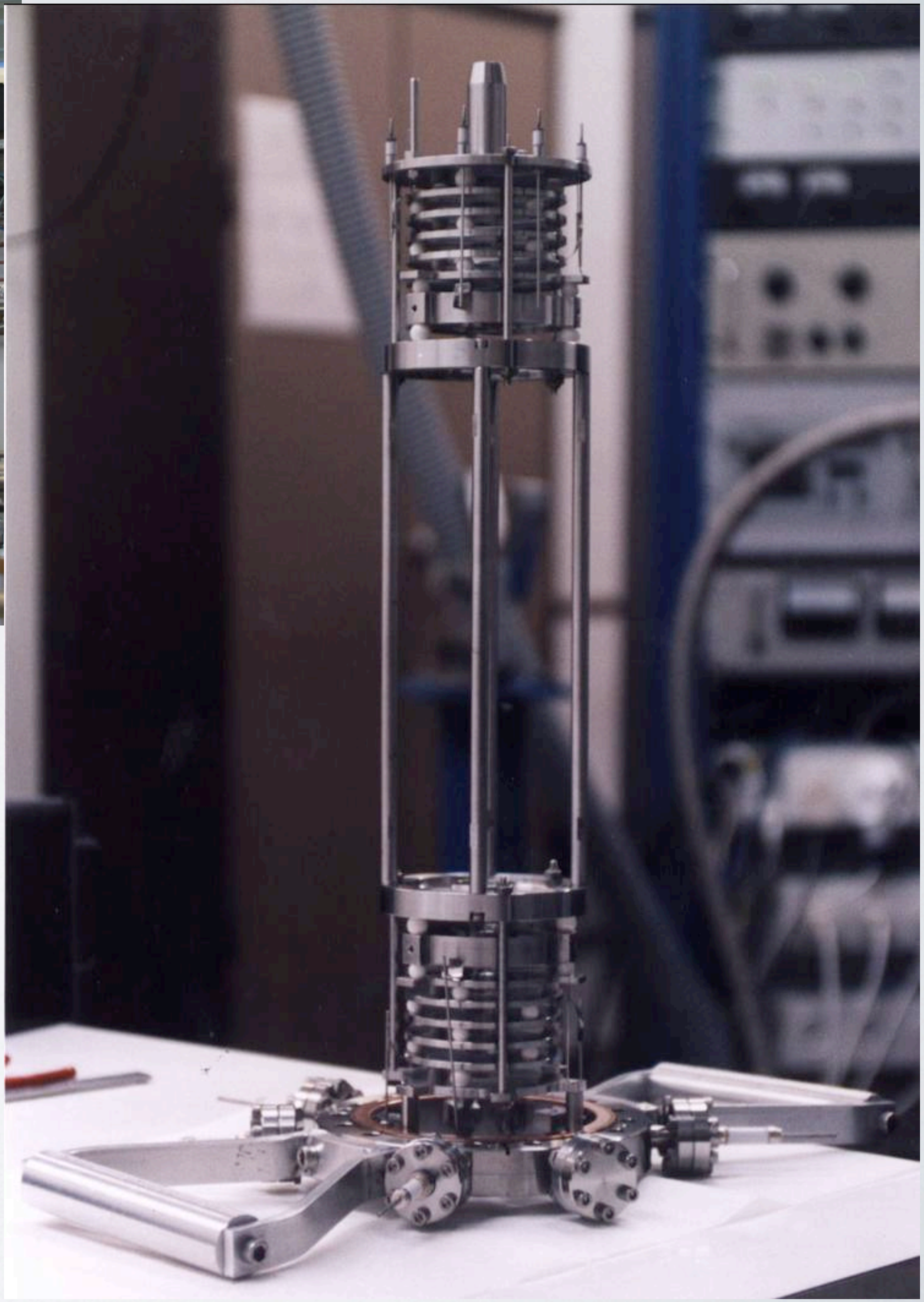


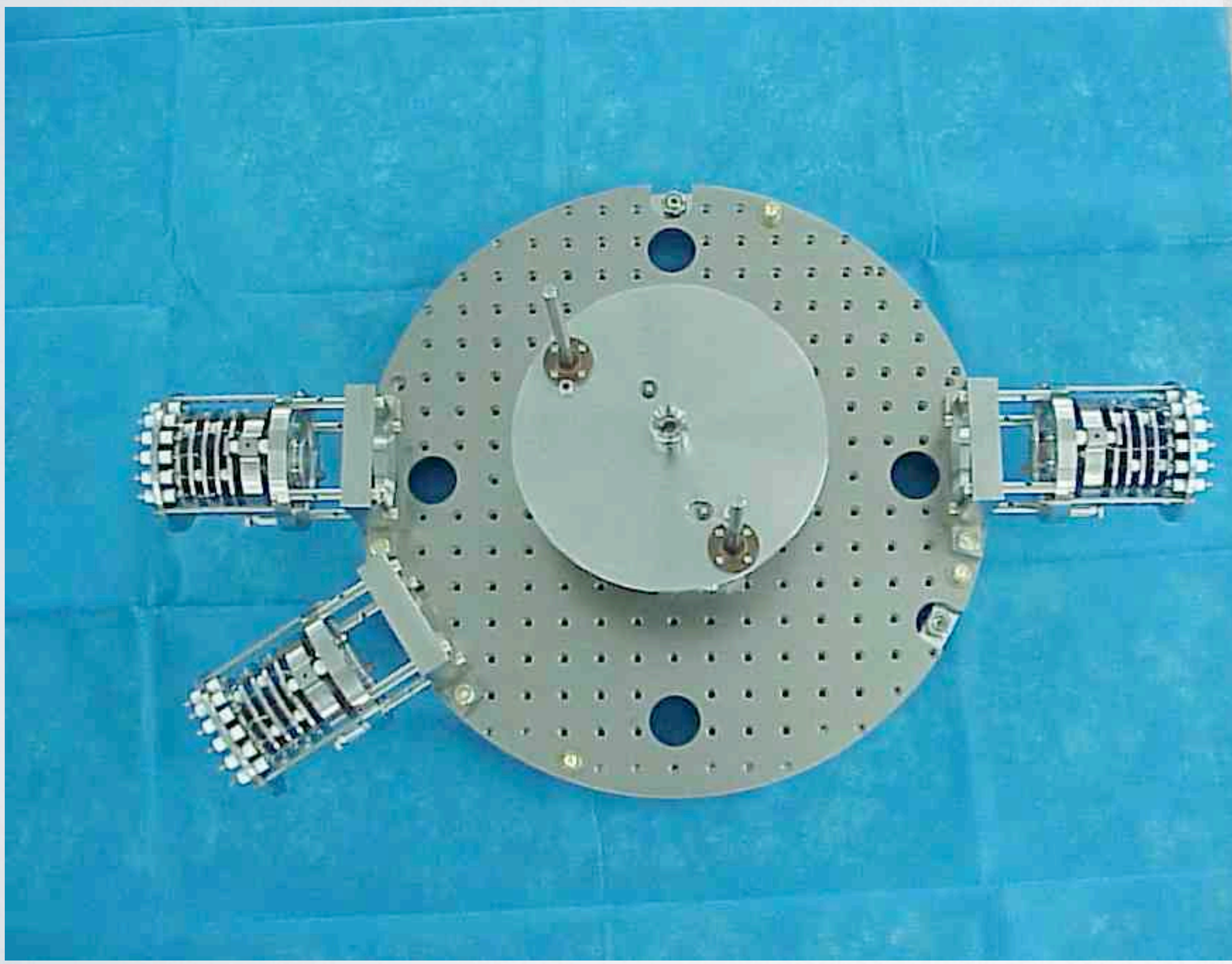
Realized at the Weizmann Institute (Israel). Also used in a cryogenic setup in Heidelberg.

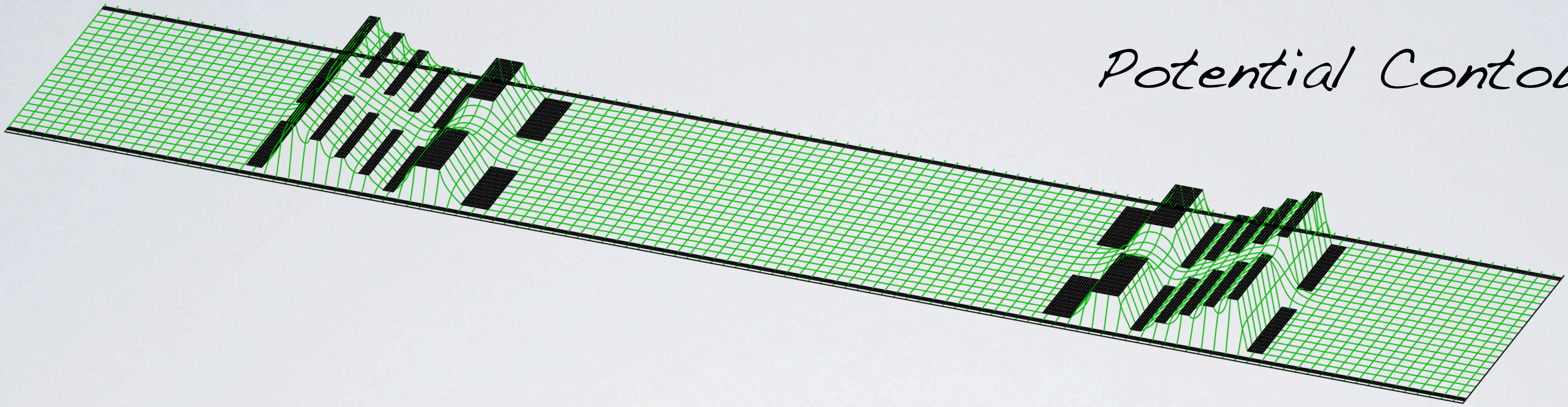




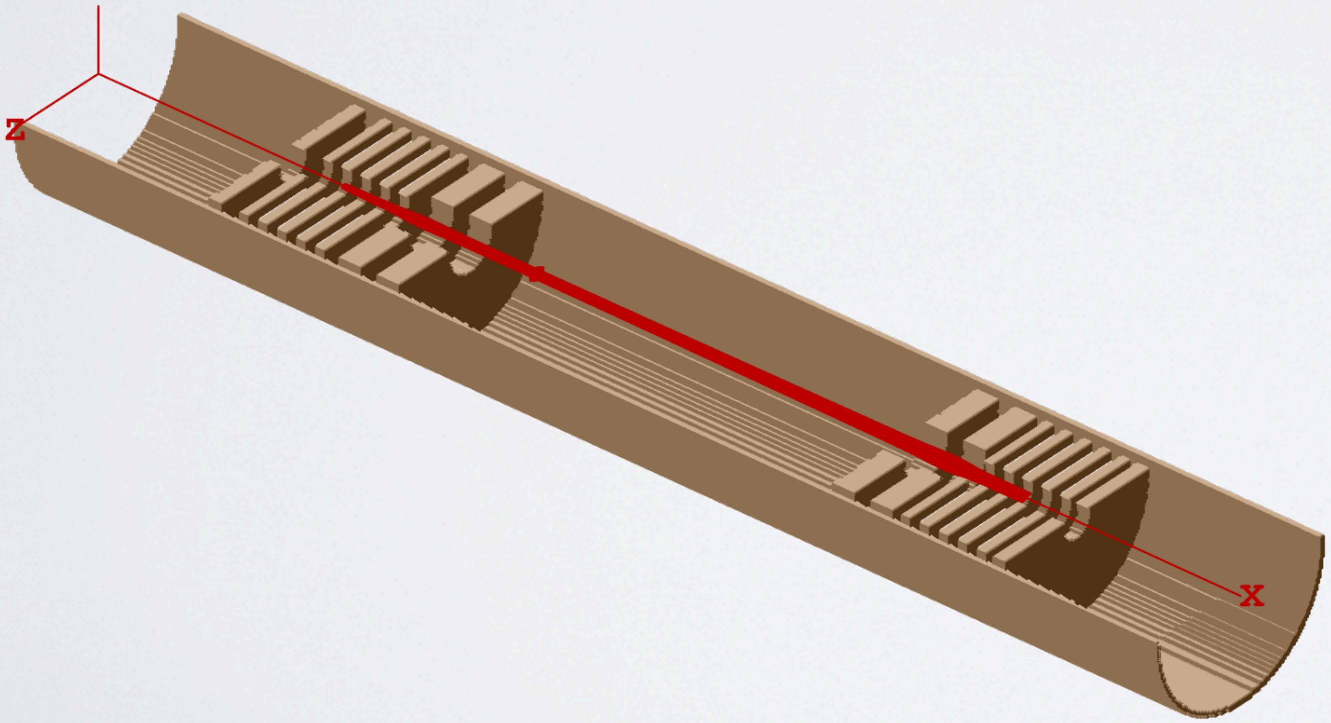








Potential Contours



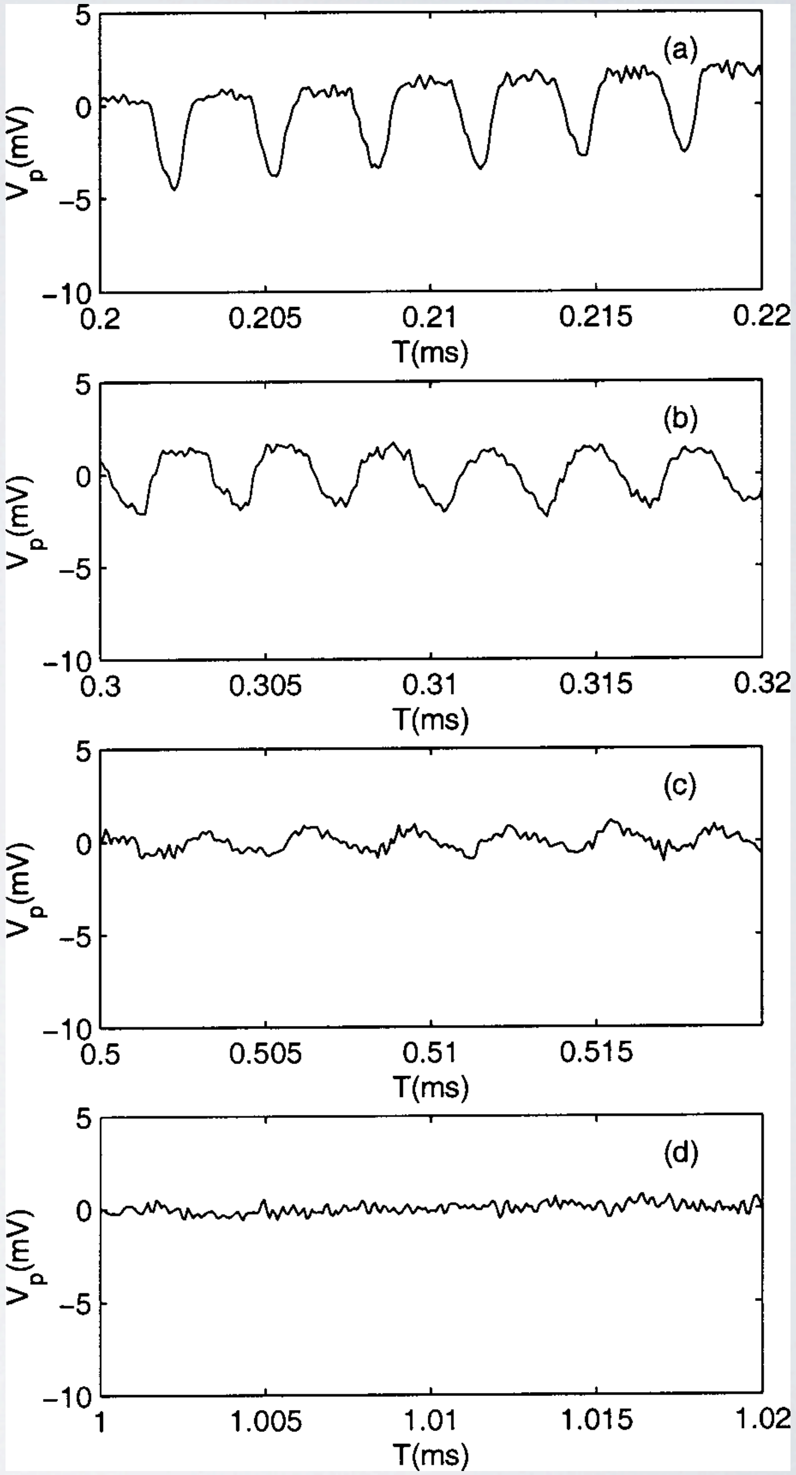
Simulated Ions in Trap

Ion Behavior In the Trap

From simple arguments the width of the ion cloud in the trap should
increase as a function of the oscillation number (not all ion have the exact same energy).

$$W_n = (W_0^2 + n^2 \Delta T^2)^{1/2}$$

Signal in pickup electrode for different times after injection.



D. Zajfman et al., J. Opt. Soc. Am. B20, 1028 (2003)

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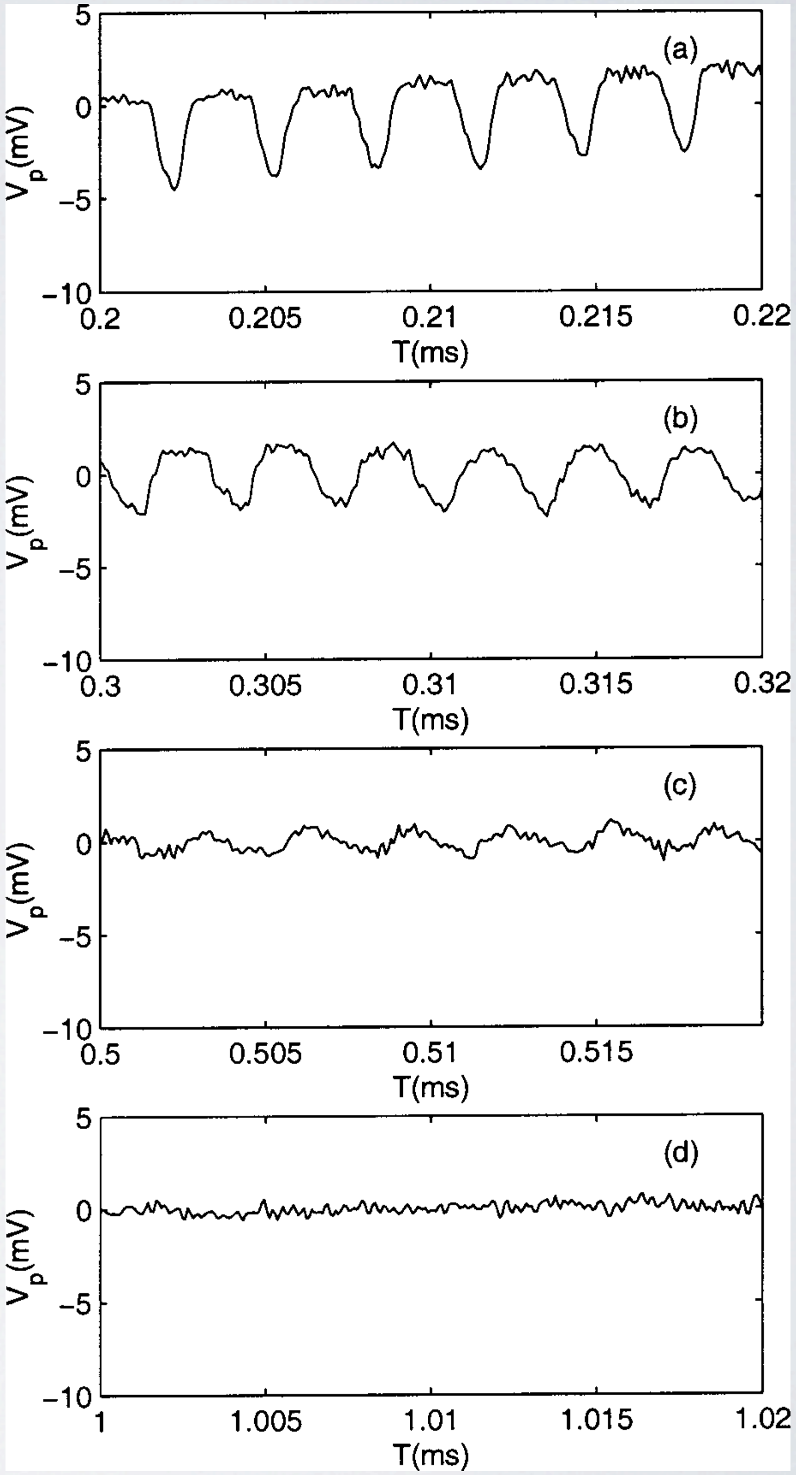
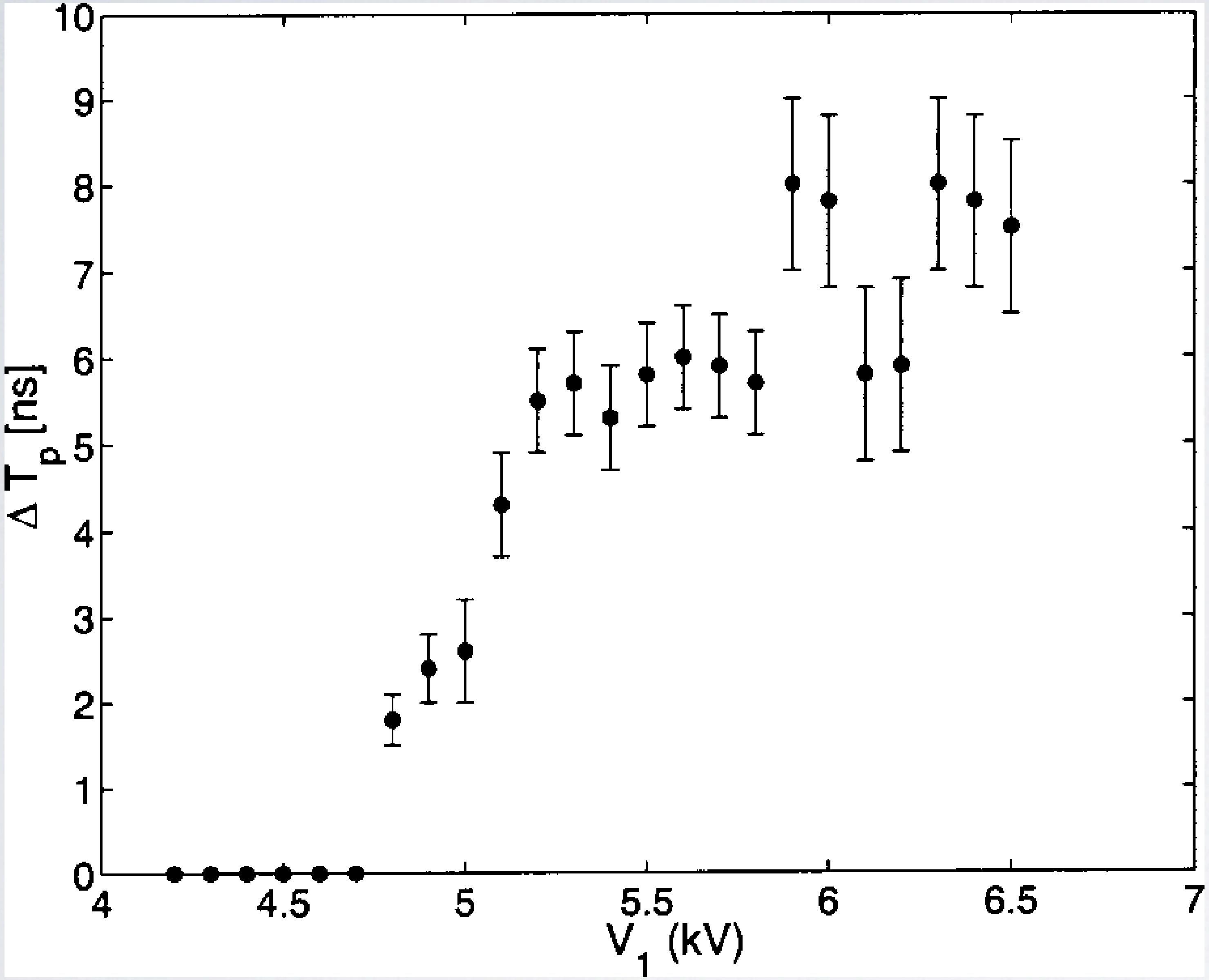


Using the pickup, it is possible to measure the detuning coefficient for different values of the (outer) electrode potential.

D. Zajfman et al., J. Opt. Soc. Am. B20, 1028 (2003)

Surprise...



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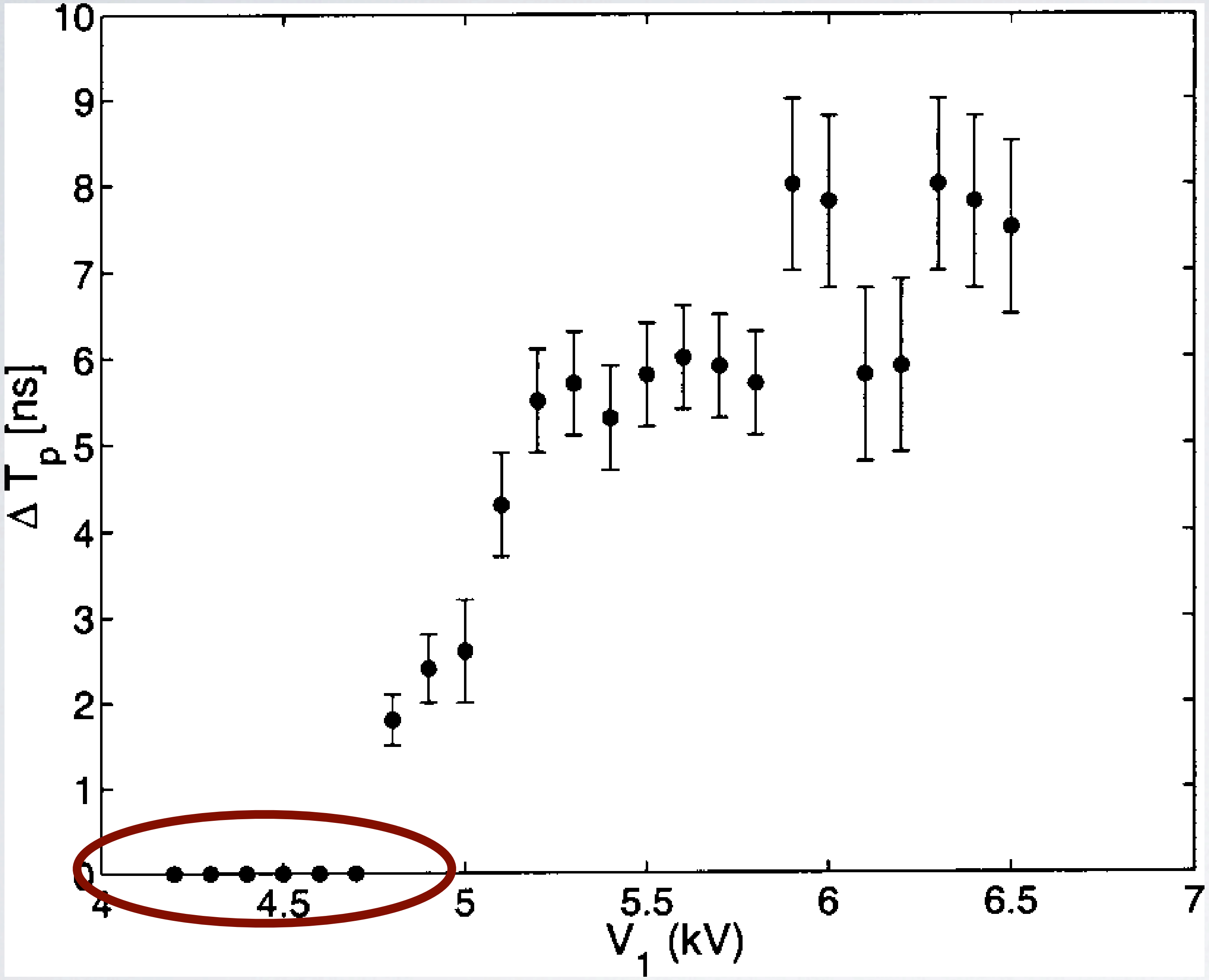

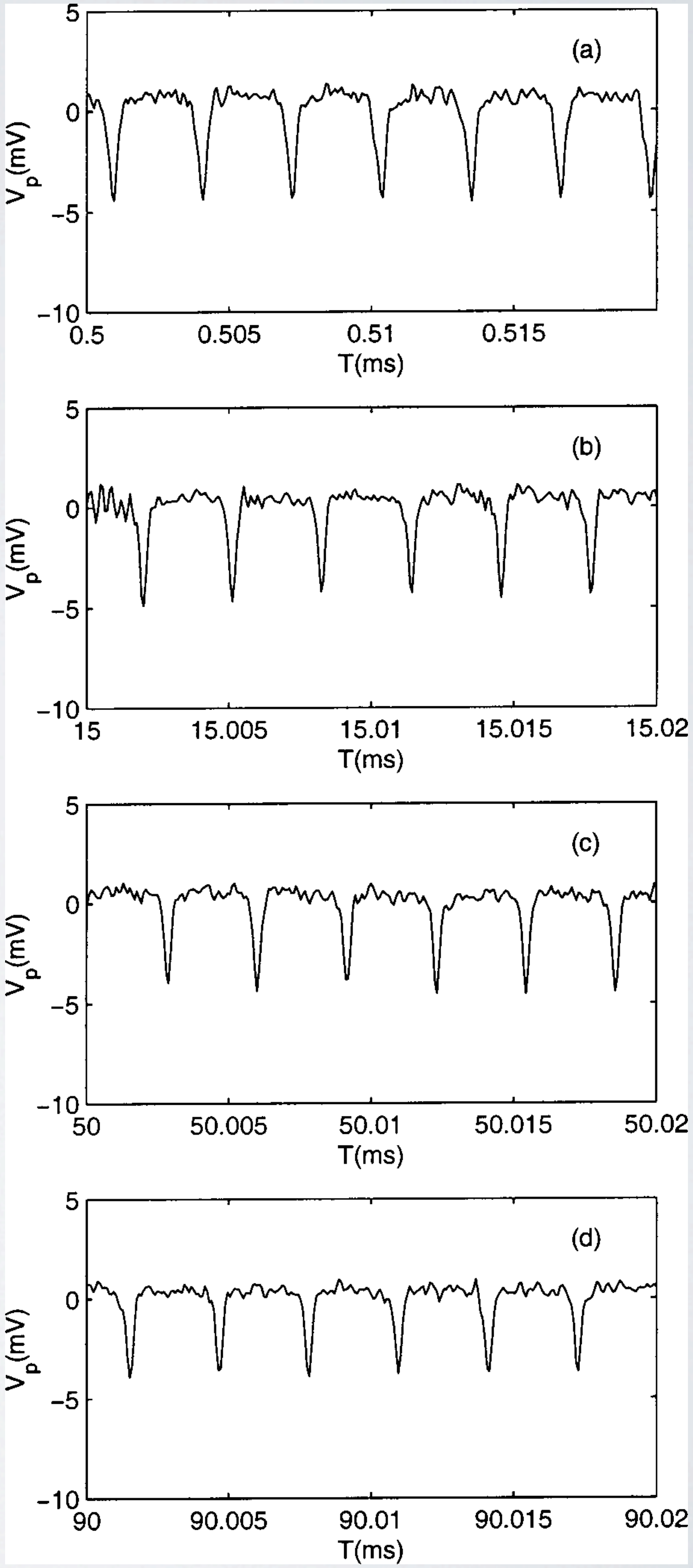

For some values of the potential there is no dispersion!

Why?

$$V(x) = \begin{cases} 0 & |x| \le L/2 \\ F(|x| - L/2) & |x| > L/2 \end{cases}$$

1D model for the potential in the trap

$$T = 4\left(\frac{L}{2\nu} + \frac{m\nu}{qF}\right)$$

Oscillation period for ion with initial velocity ν

$$\frac{dT}{d\nu} = \frac{4m}{qF} - \frac{2L}{\nu^2} = 0$$

Extremum (minimum) condition

For $V_1 < 4.75$ KV (empirically, for 4.2keV Ar^+ ions) $dT/d\nu > 0$

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Handwaving explanation (but can be "proved" analytically)

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Higher energy ions spend longer in the mirror region. On the way back they speed up the lower energy ions and get slowed by them.

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1D model for the potential in the trap

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$\frac{dT}{d\nu} = \frac{4m\ldots}{qF\ldots}$

condition

If you were an accelerator physicist you would call this: "Negative Mass Instability"

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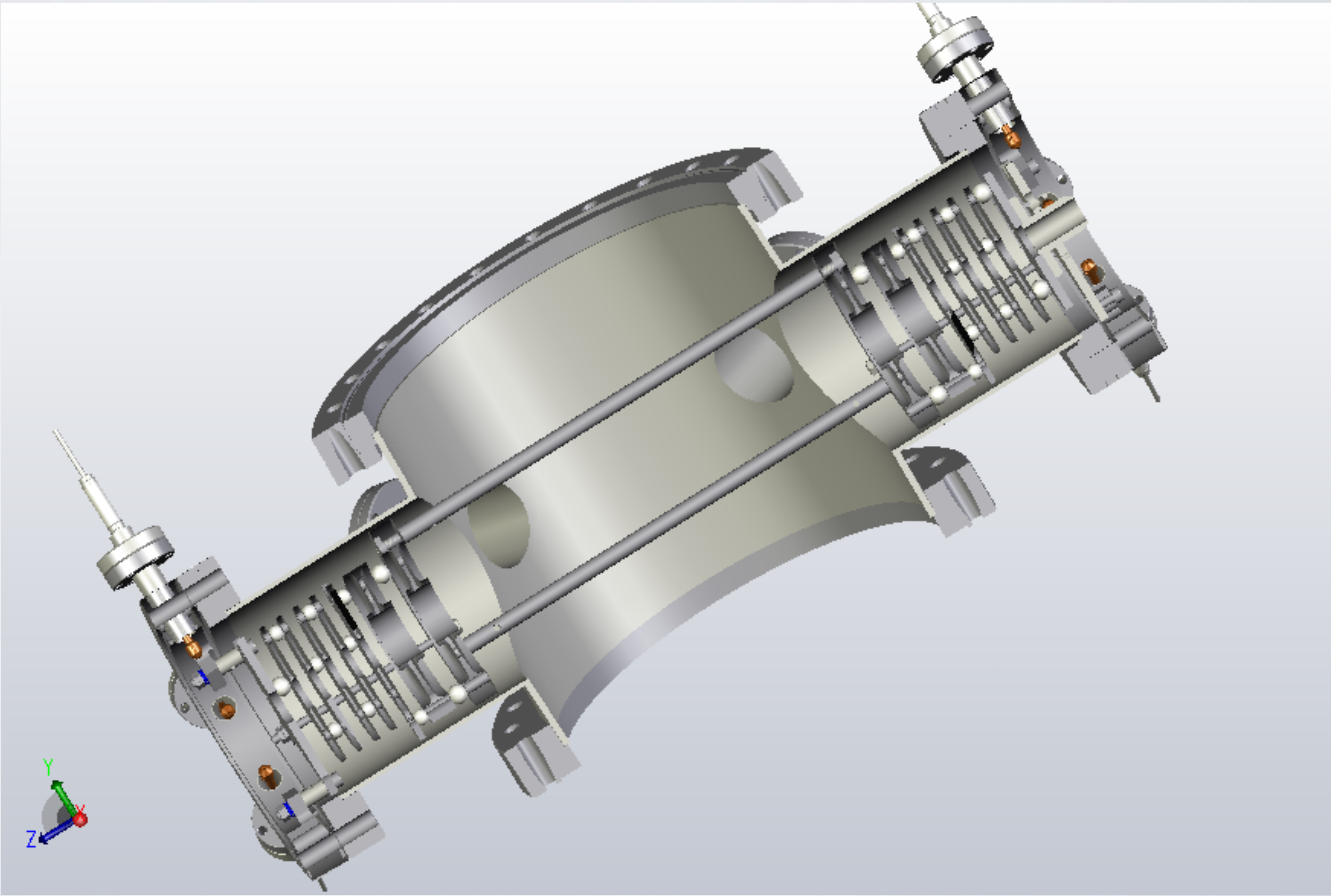
POSSIBLE APPLICATIONS

So what is it good for? (1)

Mass

Spectroscopy



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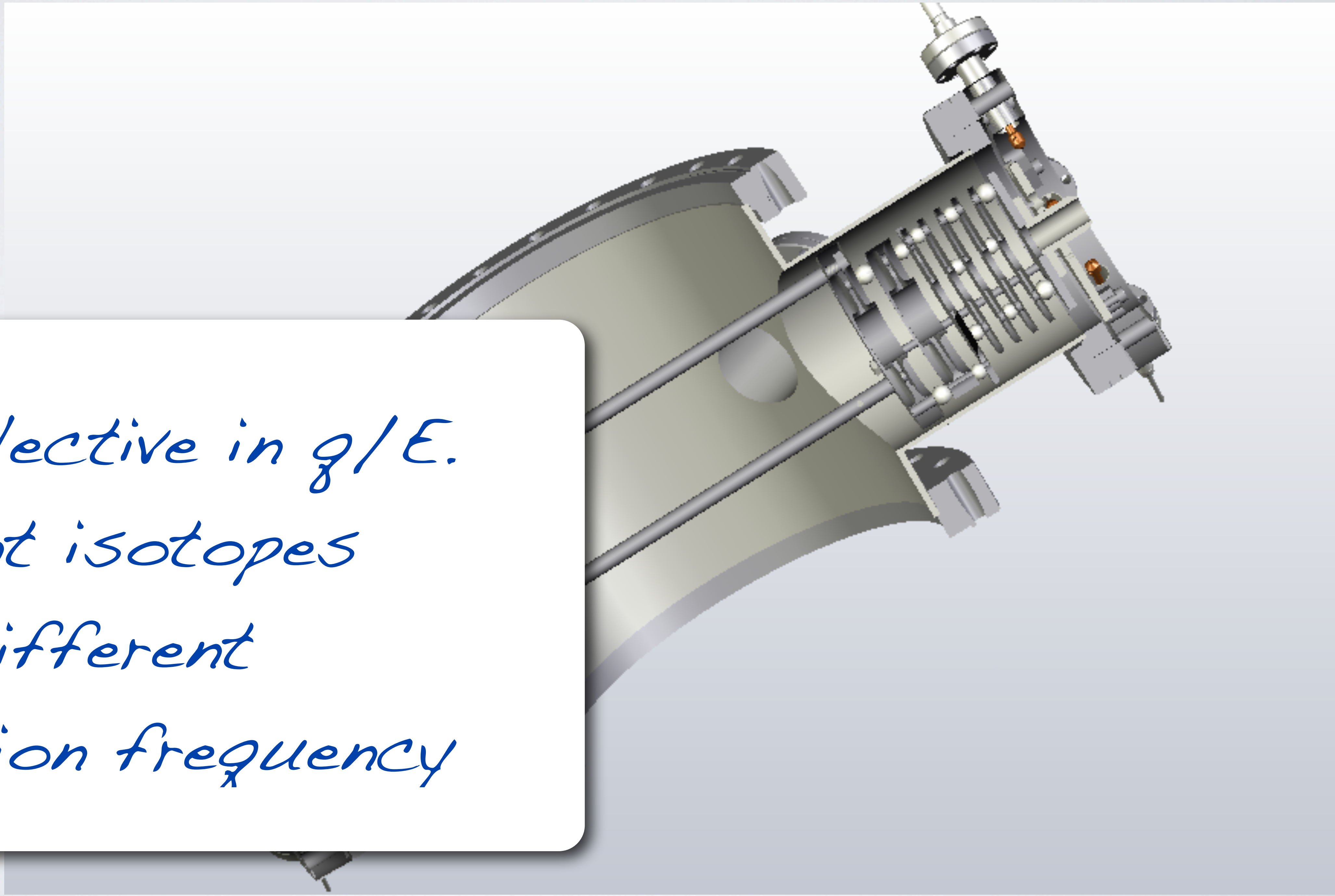

Trap selective in q/E.
Different isotopes
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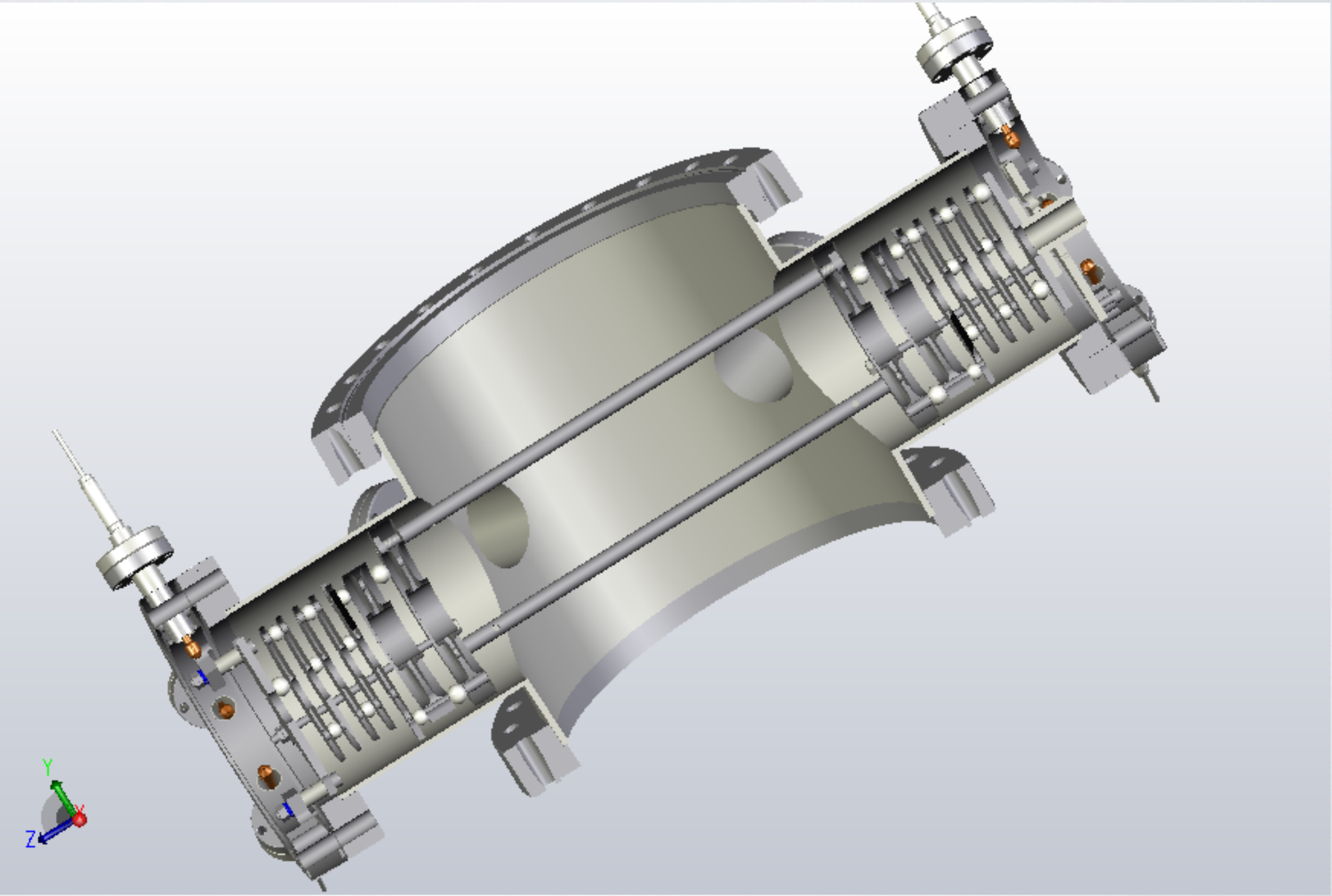

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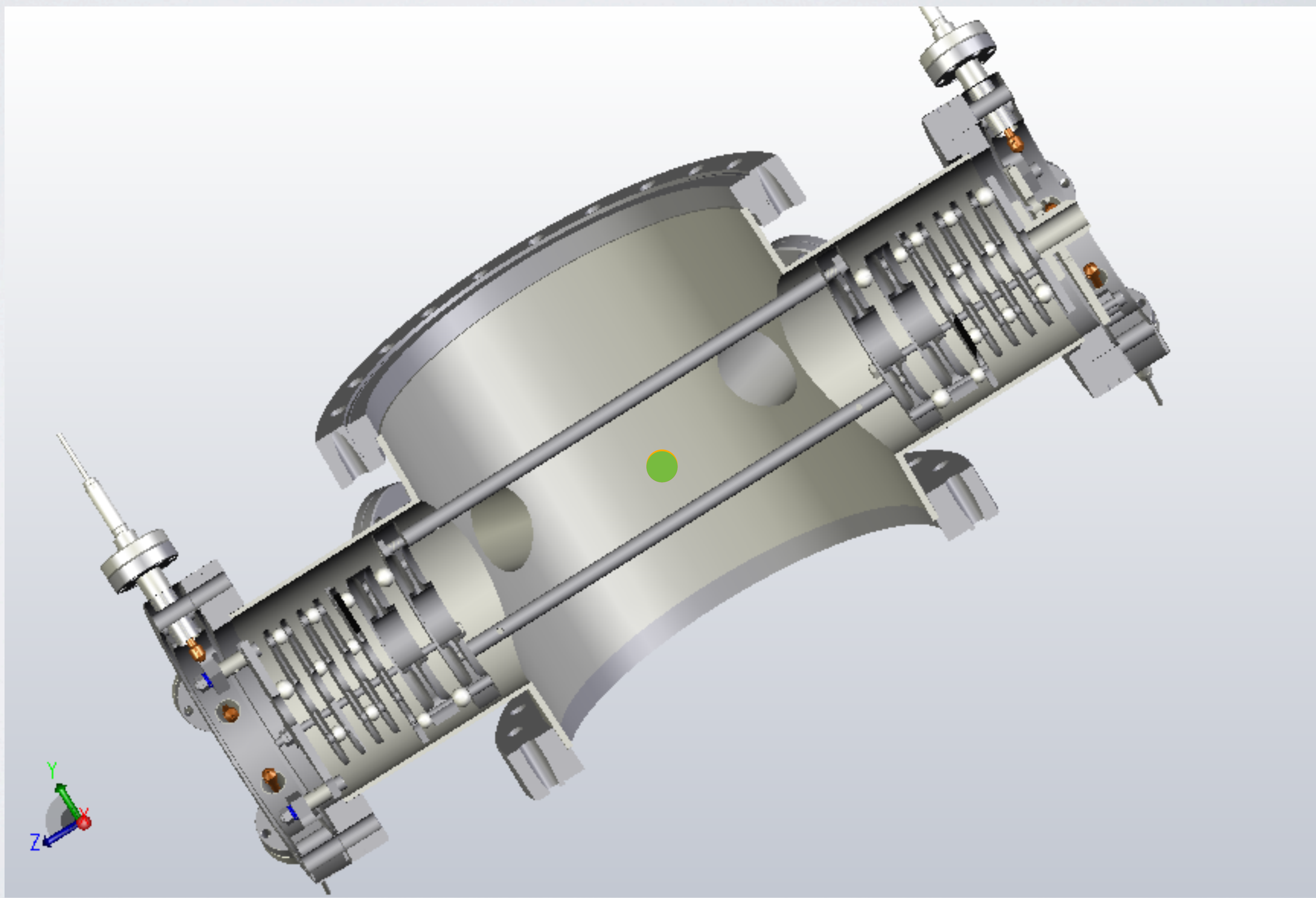

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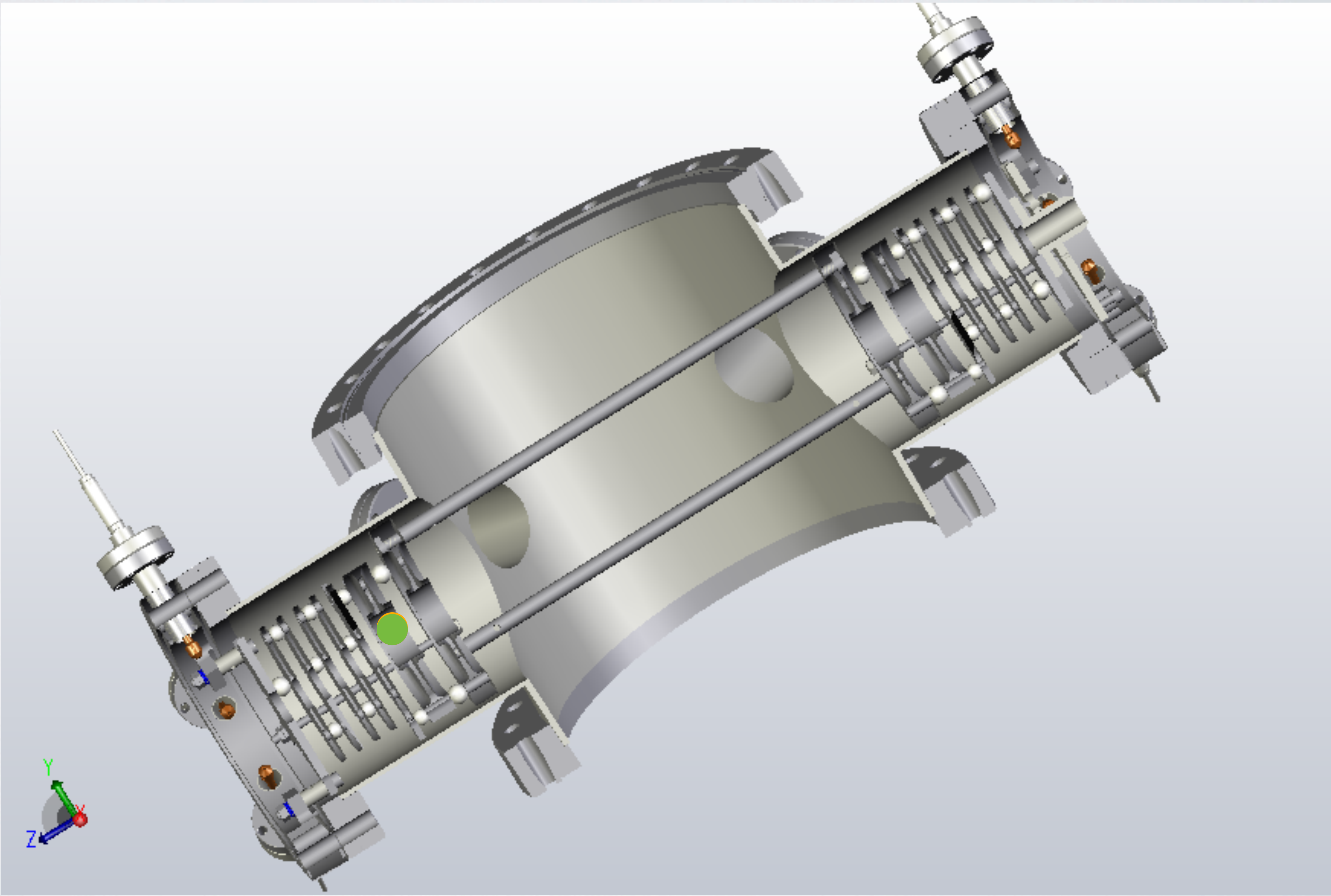

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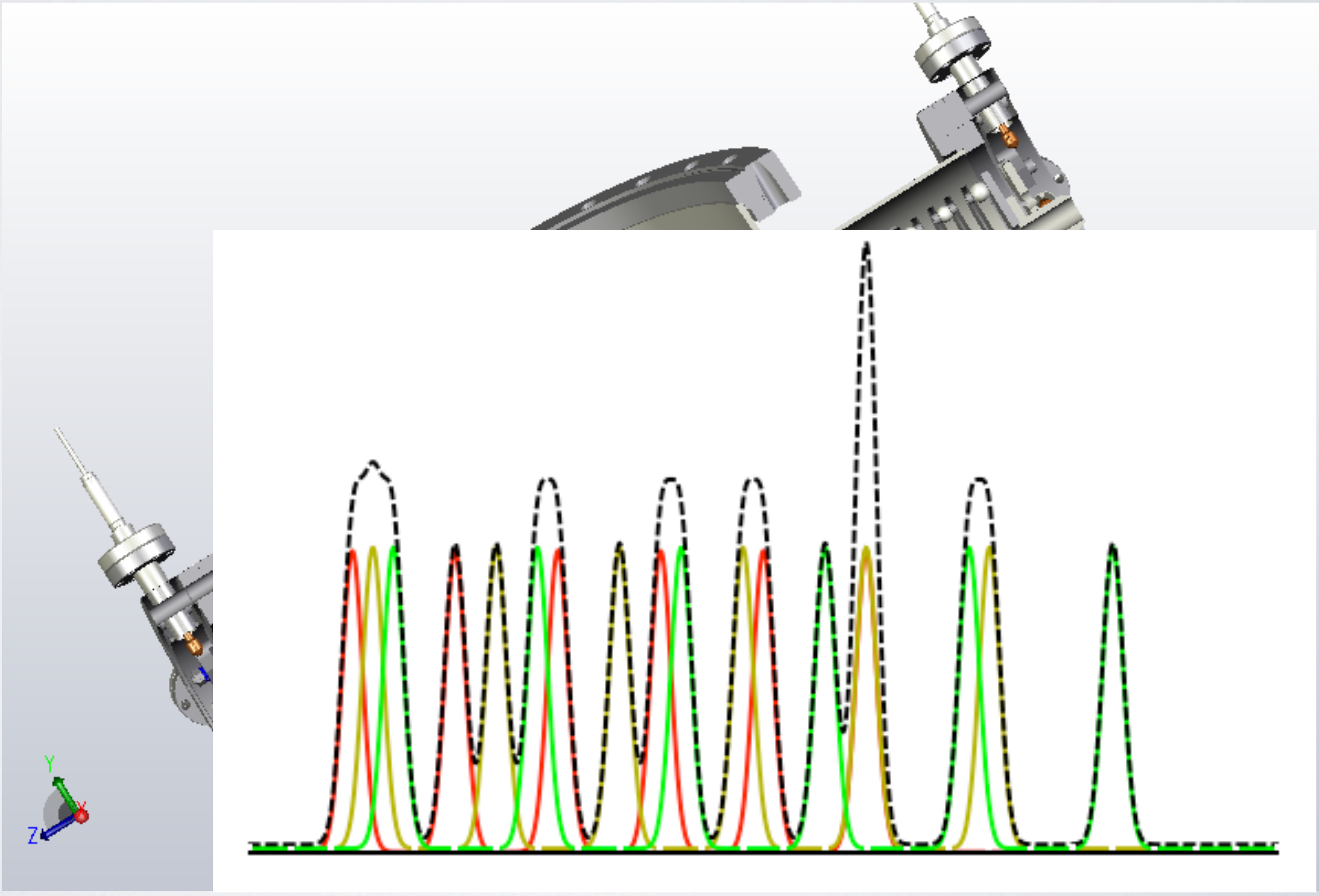
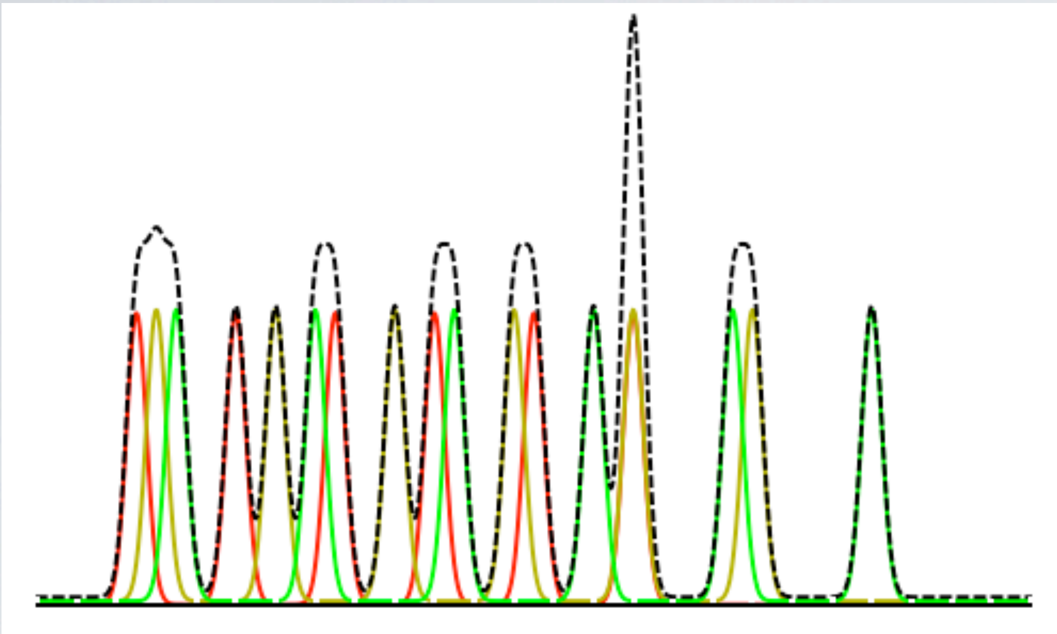


Fourier Transform the pickup charge



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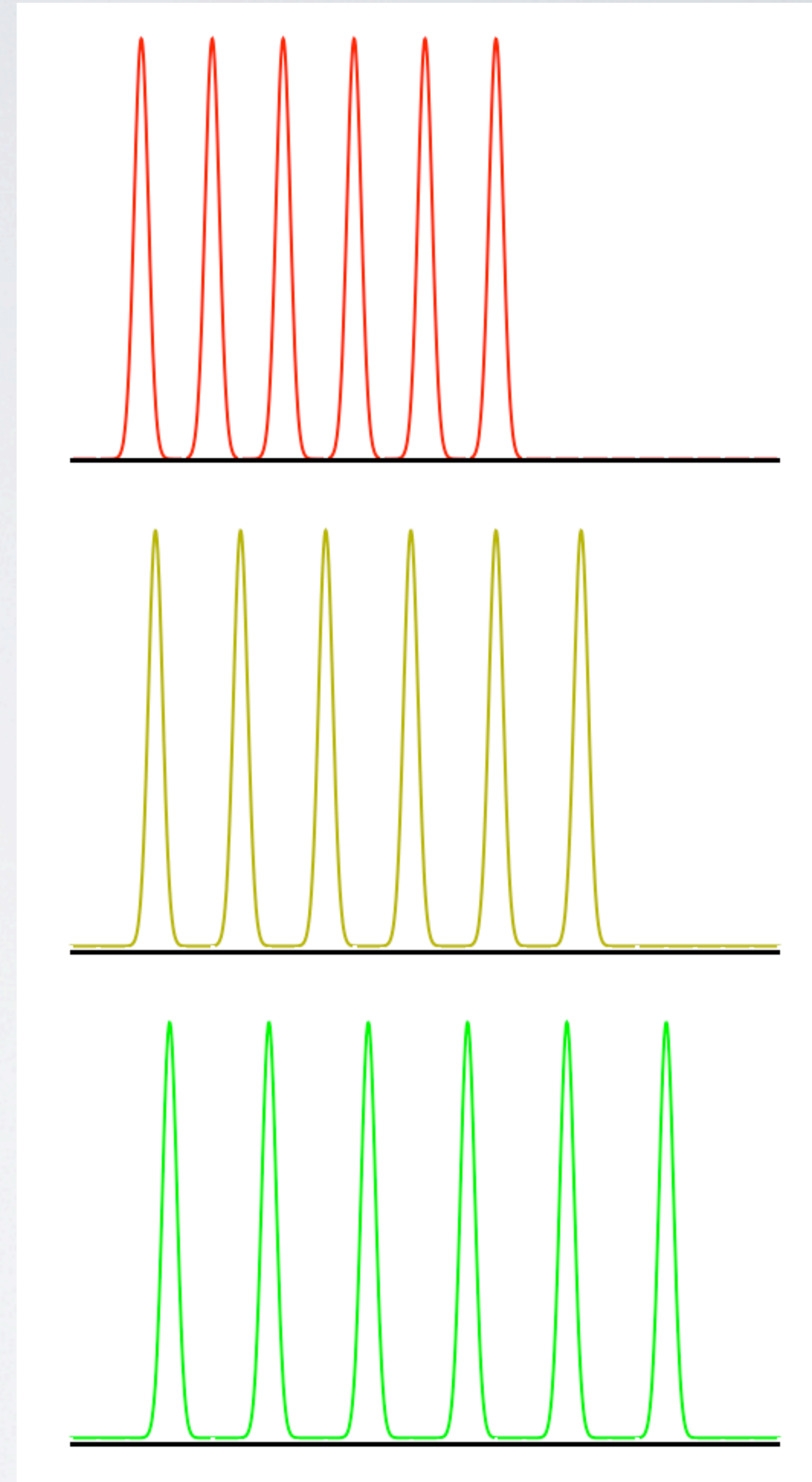

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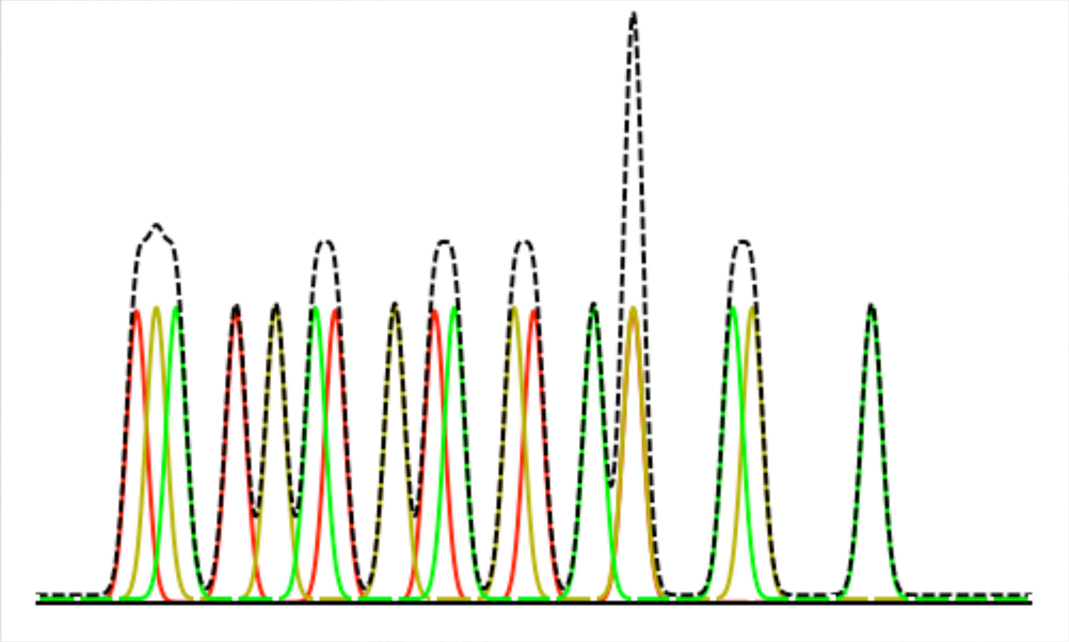

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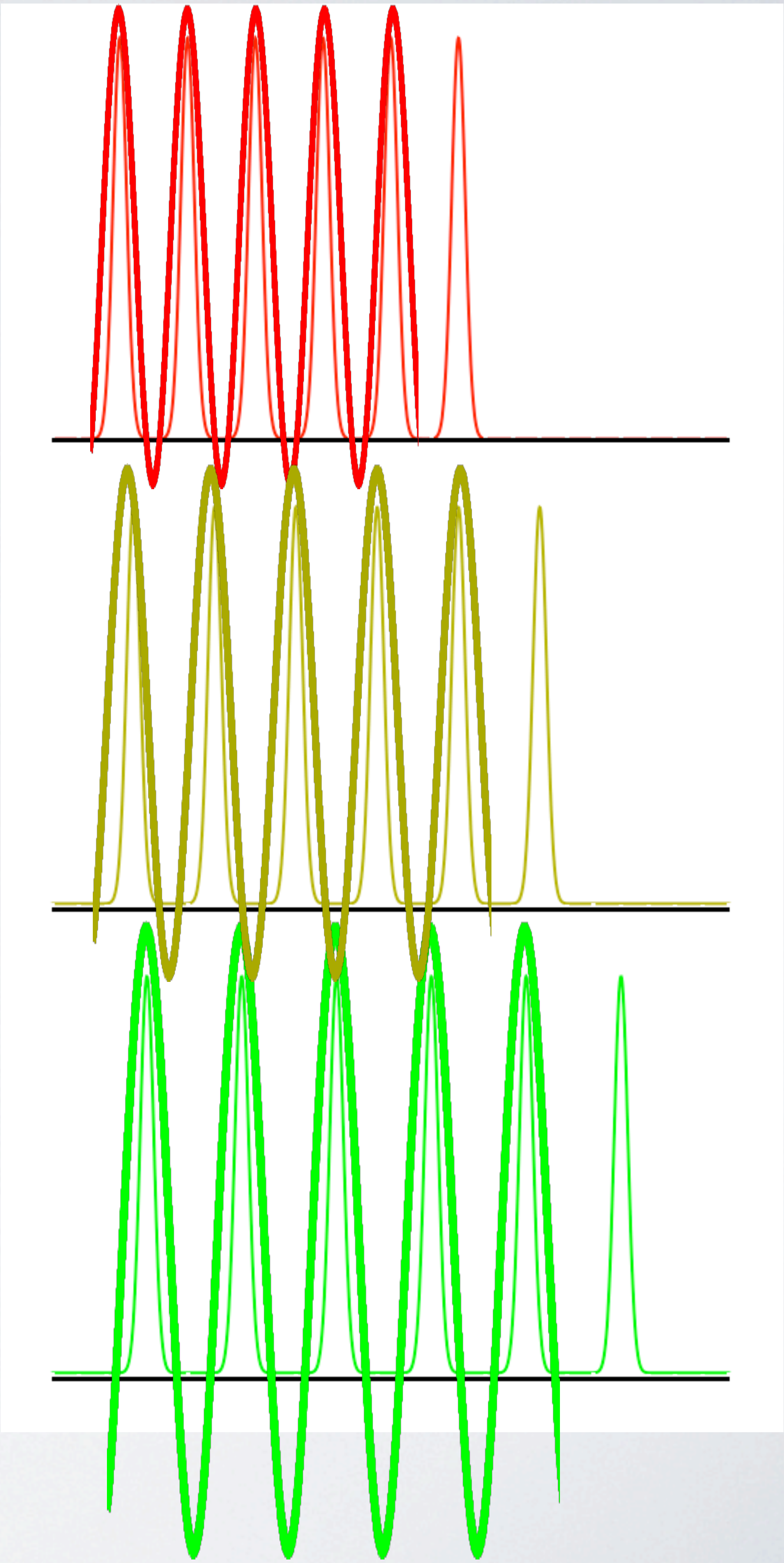

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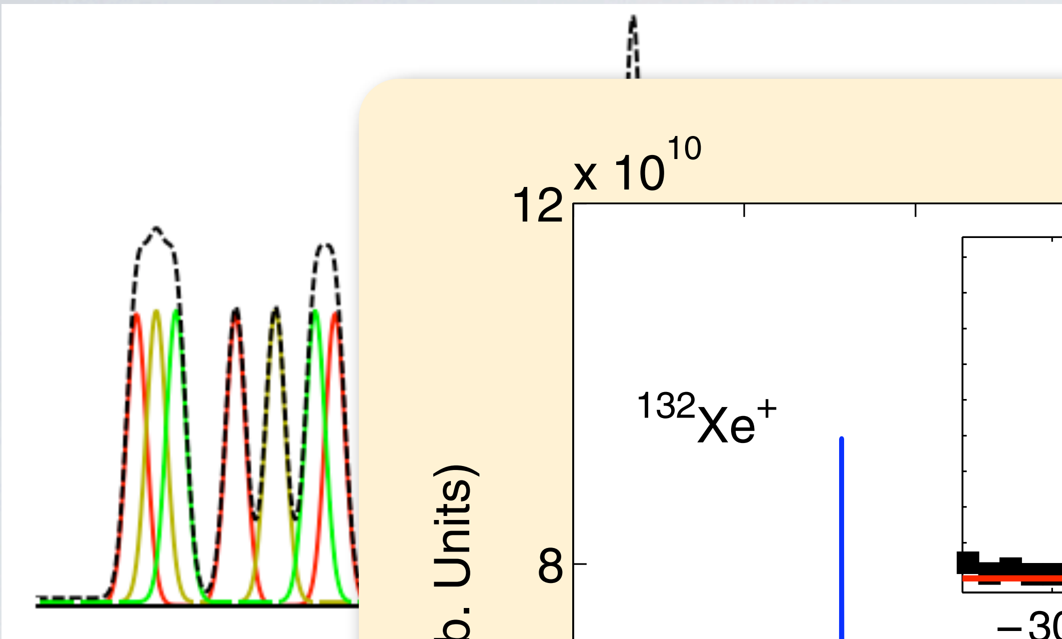

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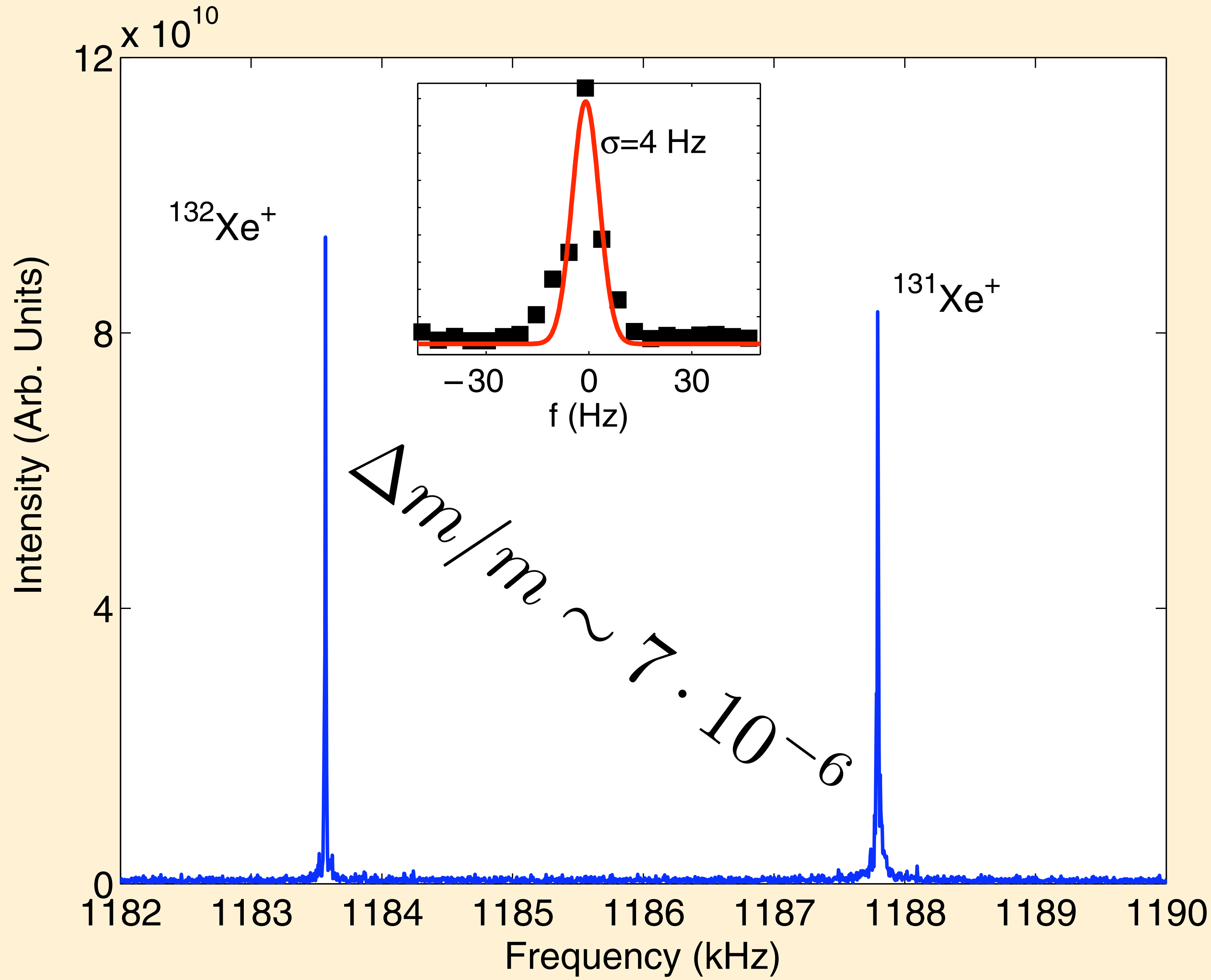
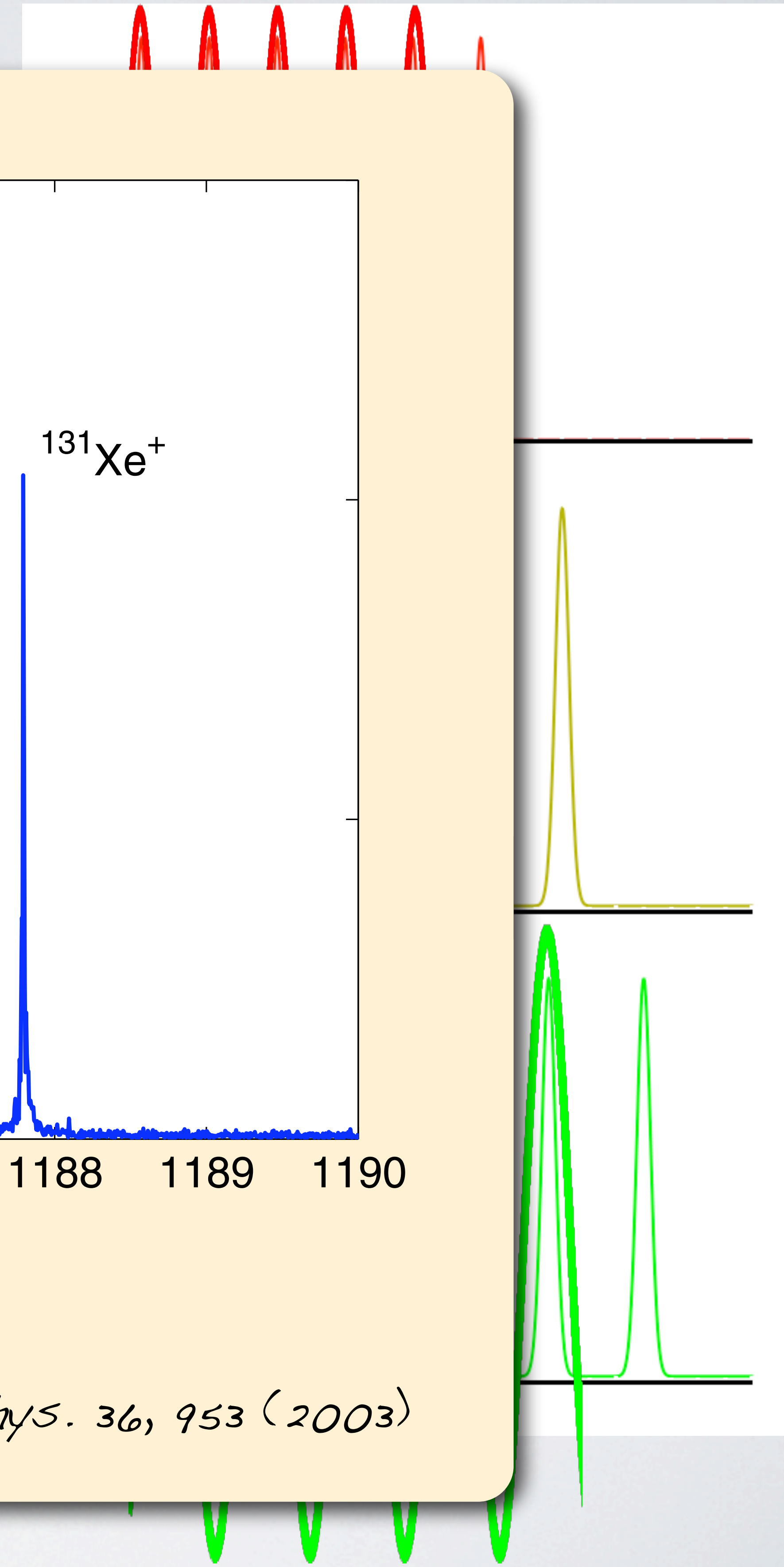
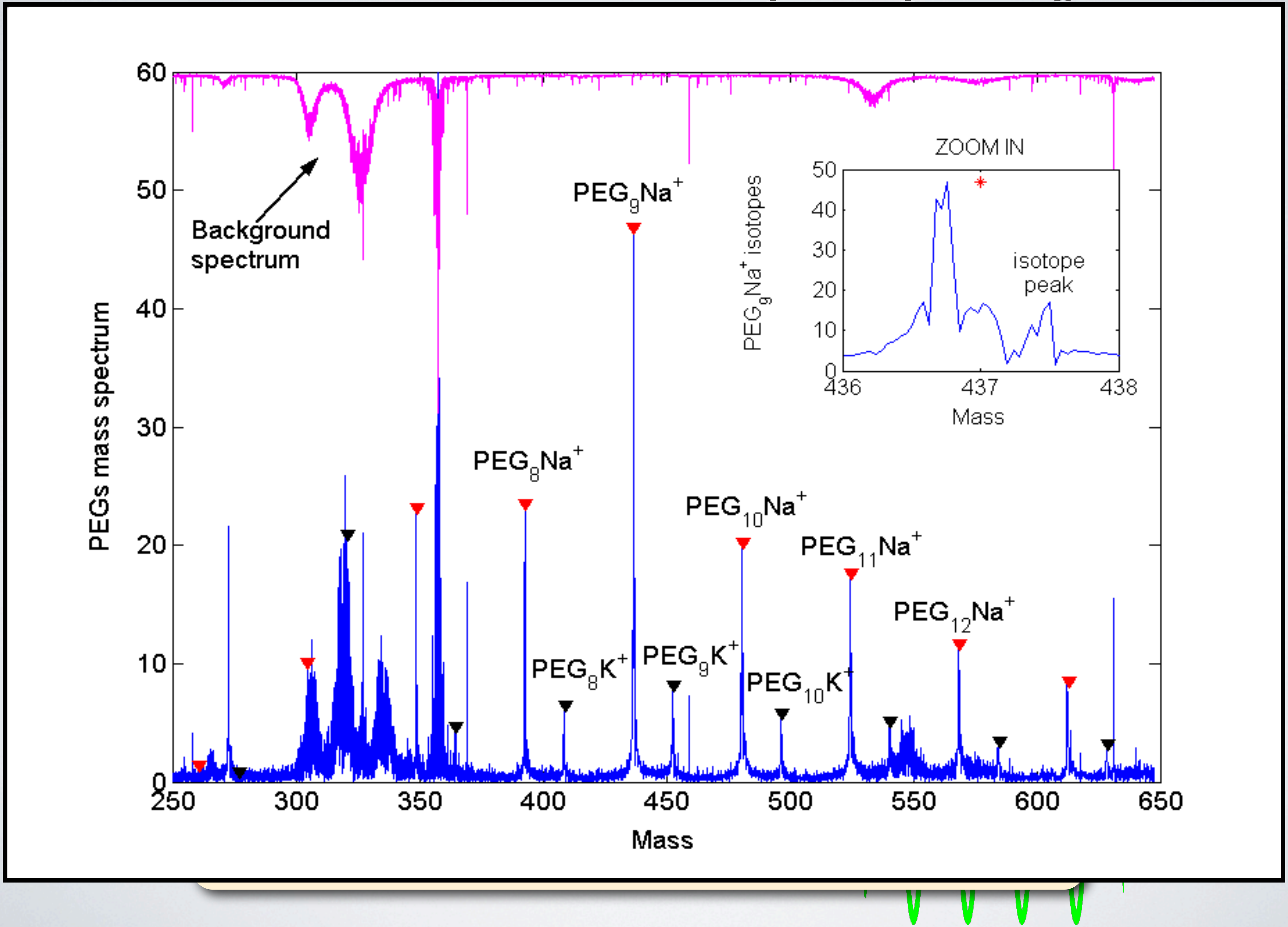


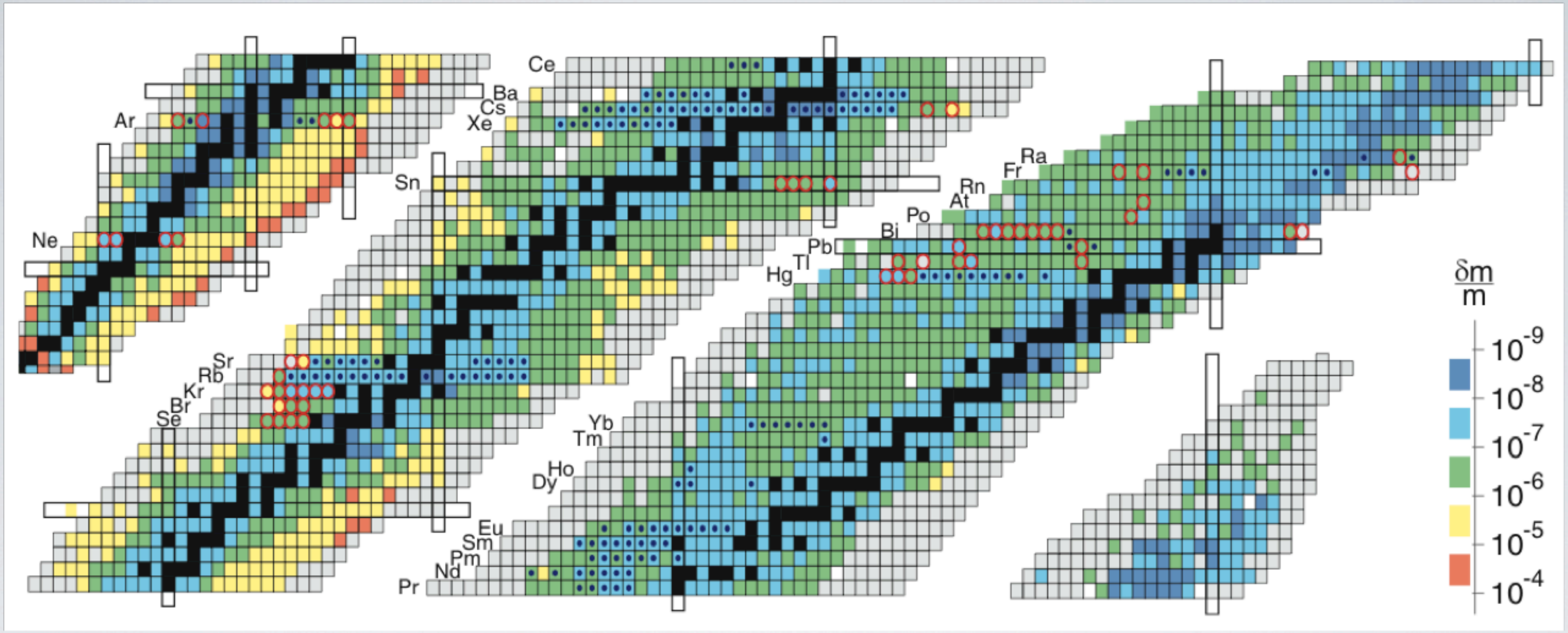
D. Strasser J. Phys. B: At. Mol. Opt. Phys. 36, 953 (2003)



Fourier Transform the pickup charge

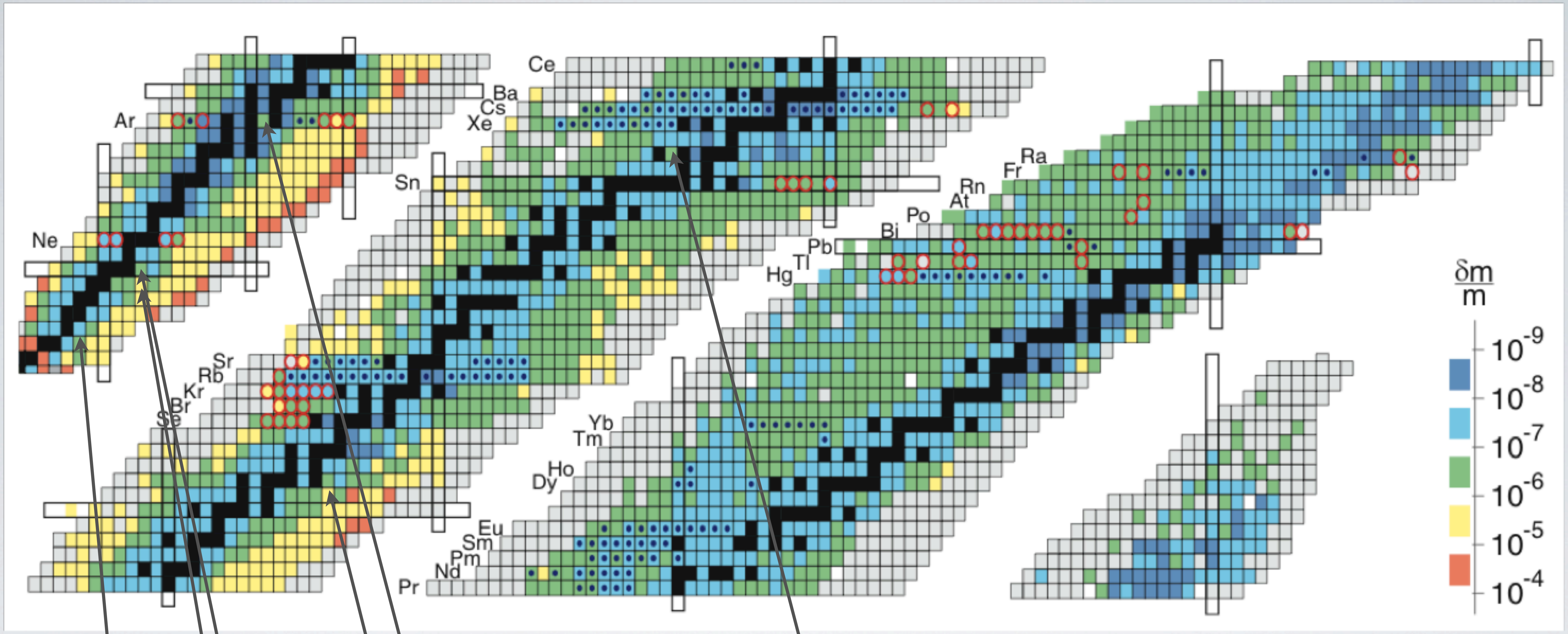


World Mass Resolutions



F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)

World Mass Resolutions



^{19}O (26 sec)

^{39}Ar (269 yr)

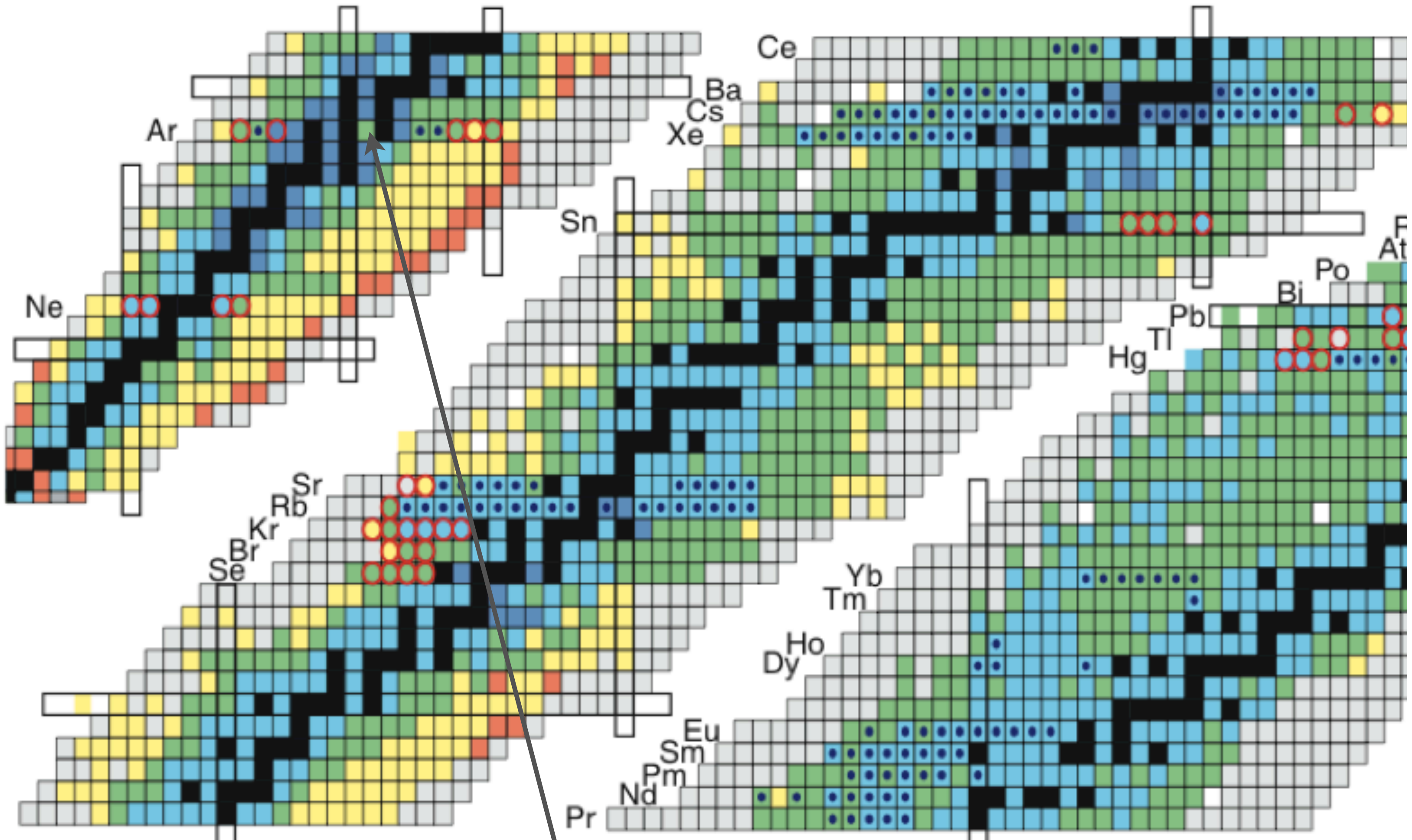
^{121}Te (19 days)

^{11}Be (14 sec)

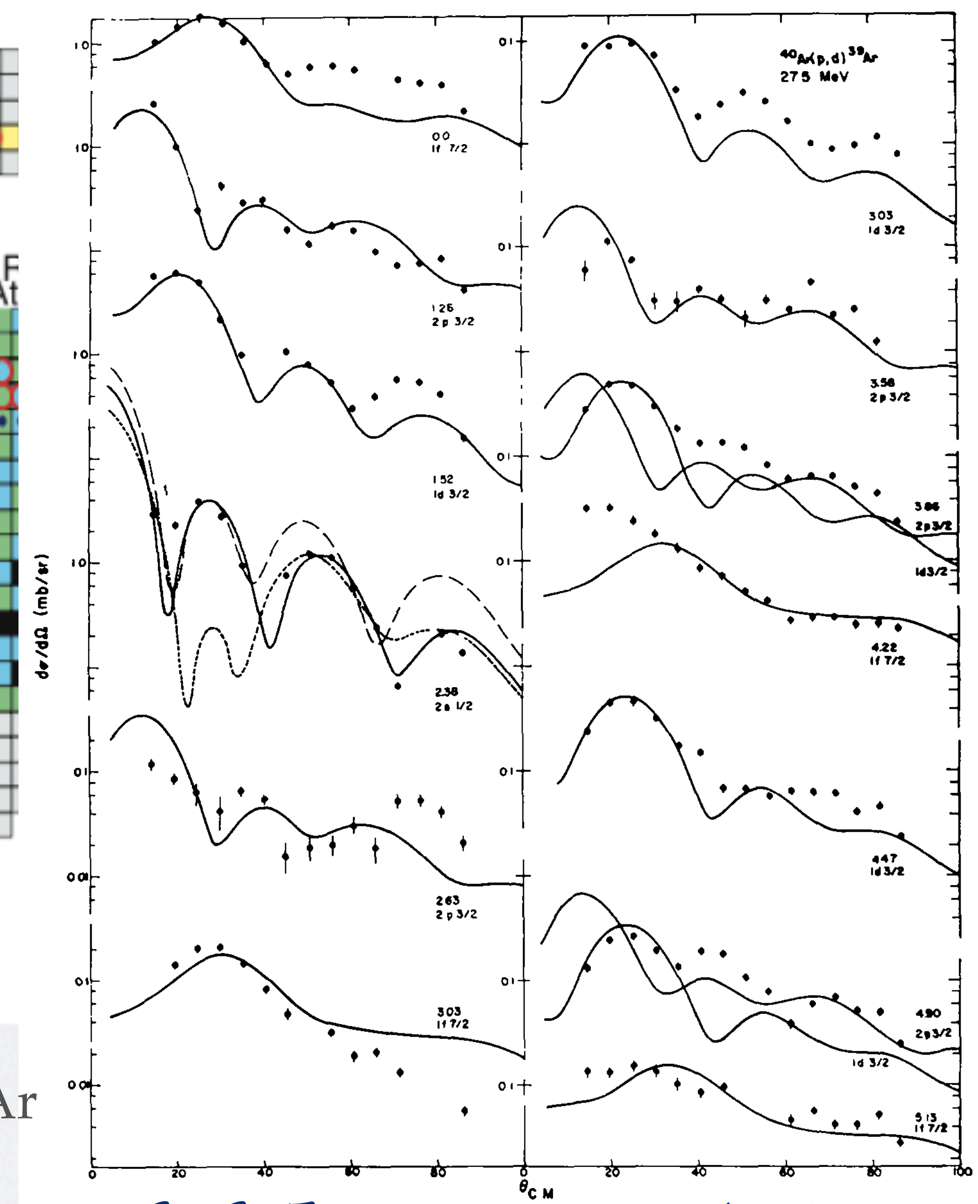
^{18}N (622 msec)

^{70}Cu (4.5 sec)

F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)



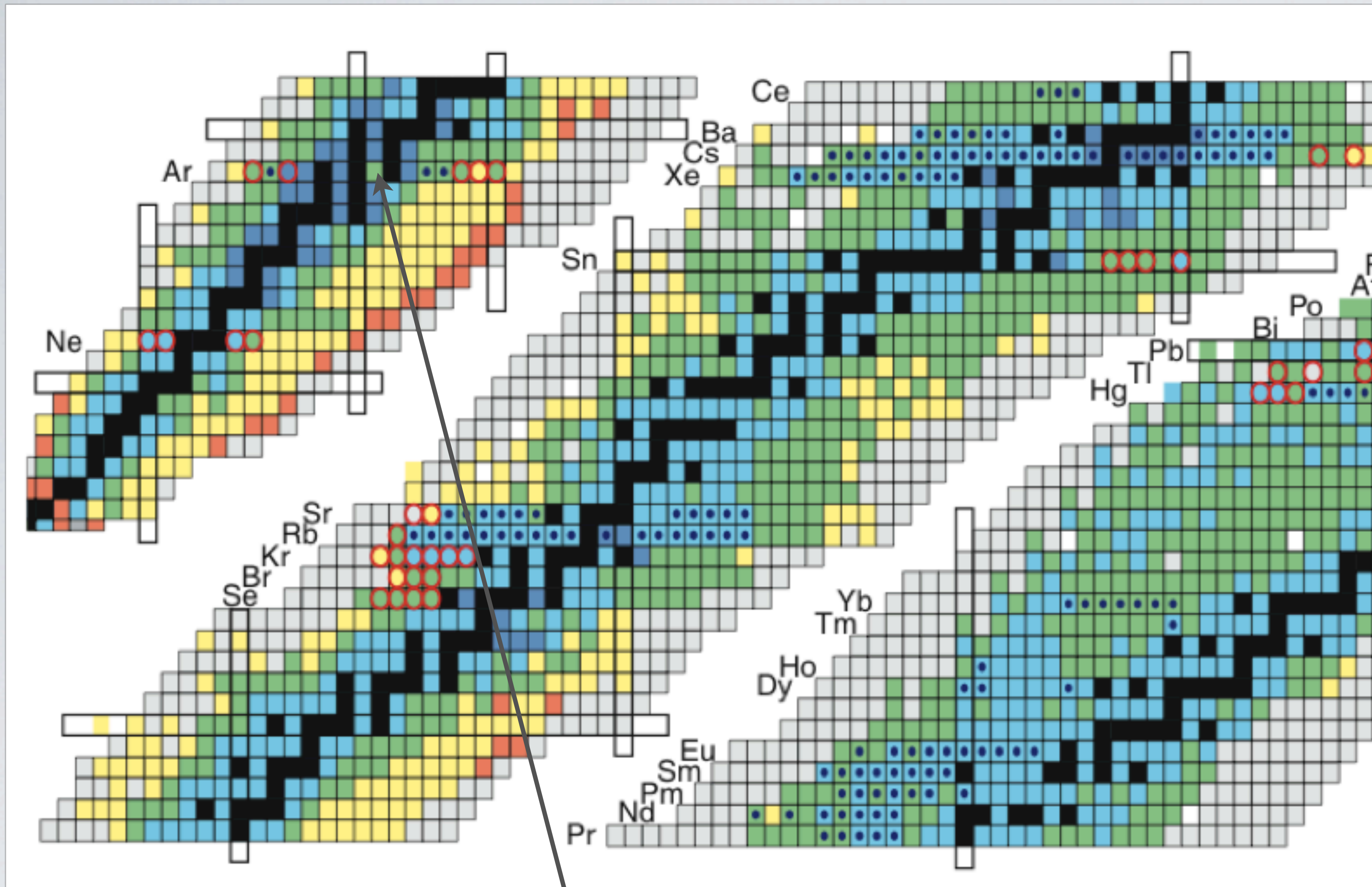
^{39}Ar
(269 yr)

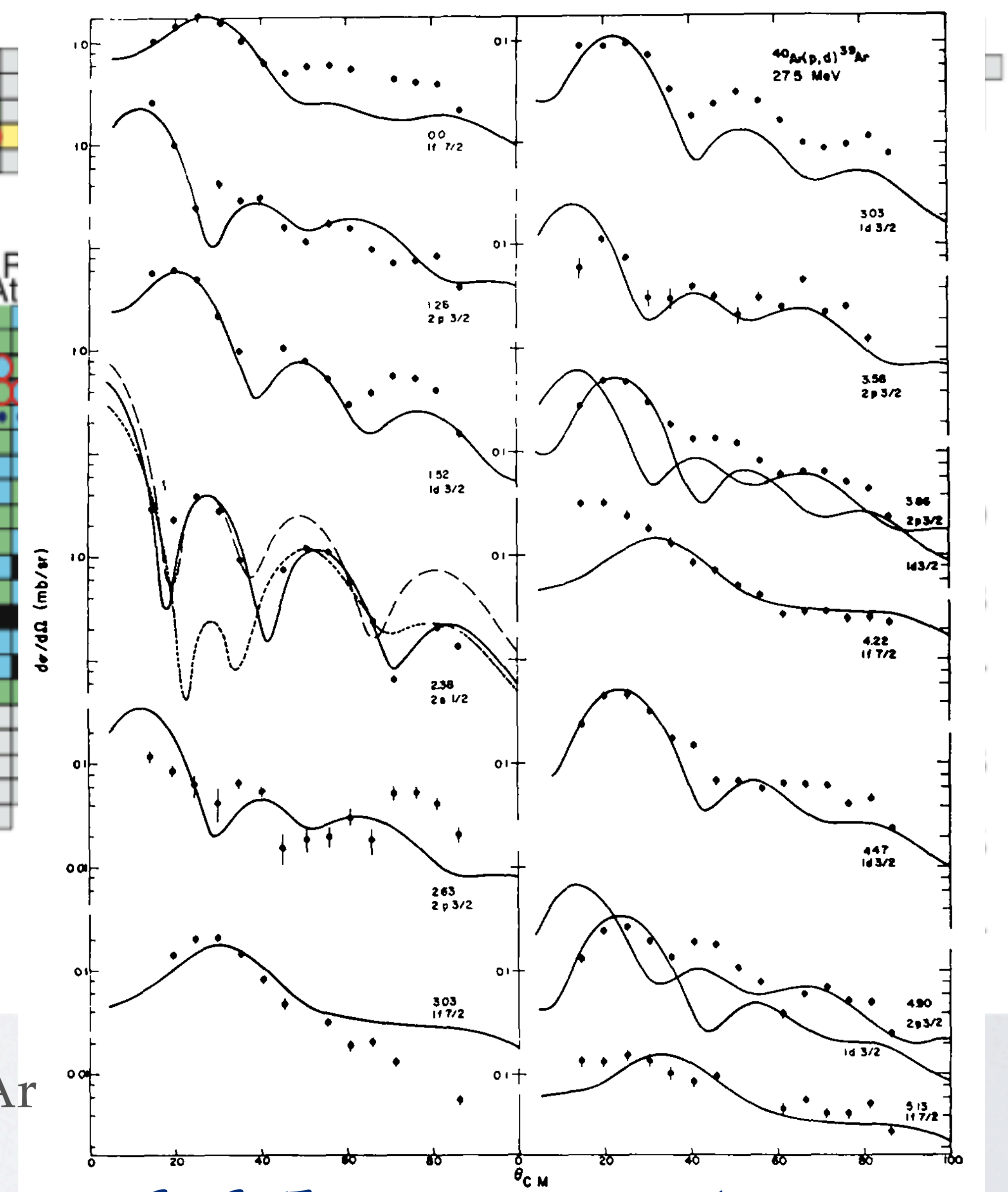


- Produced via $^{40}Ar(p,d)^{39}Ar$ with ~27 MeV protons.
- ^{40}Ar pretty much the easiest stuff to get.
- Long lived - easy transport.
- $^{38,40}Ar$ stable - perfect for calibration.
- All-in-all a good test case.

R. R. Johnson et al., Nucl Phys A108, 113 (1968)

F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)





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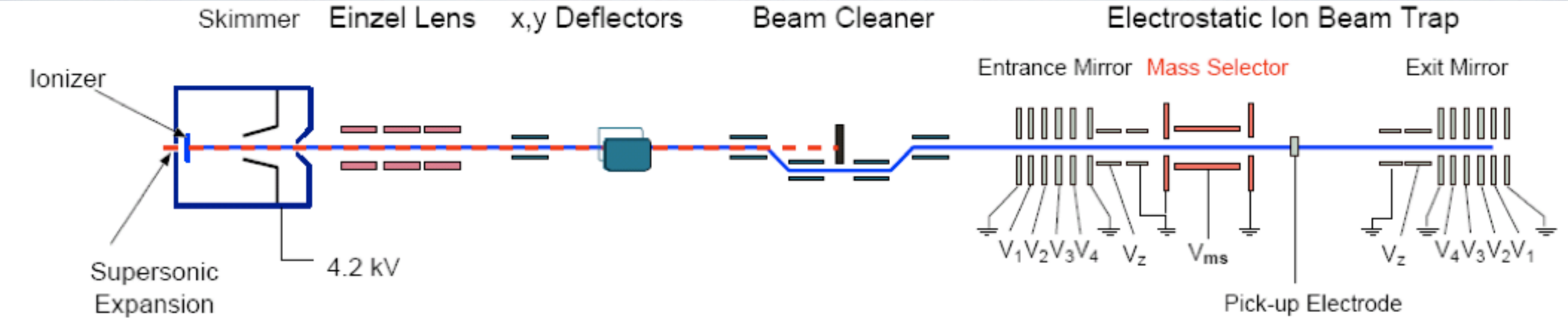
R. R. Johnson et al., Nucl Phys A108, 113 (1968)

What about superheavy elements?

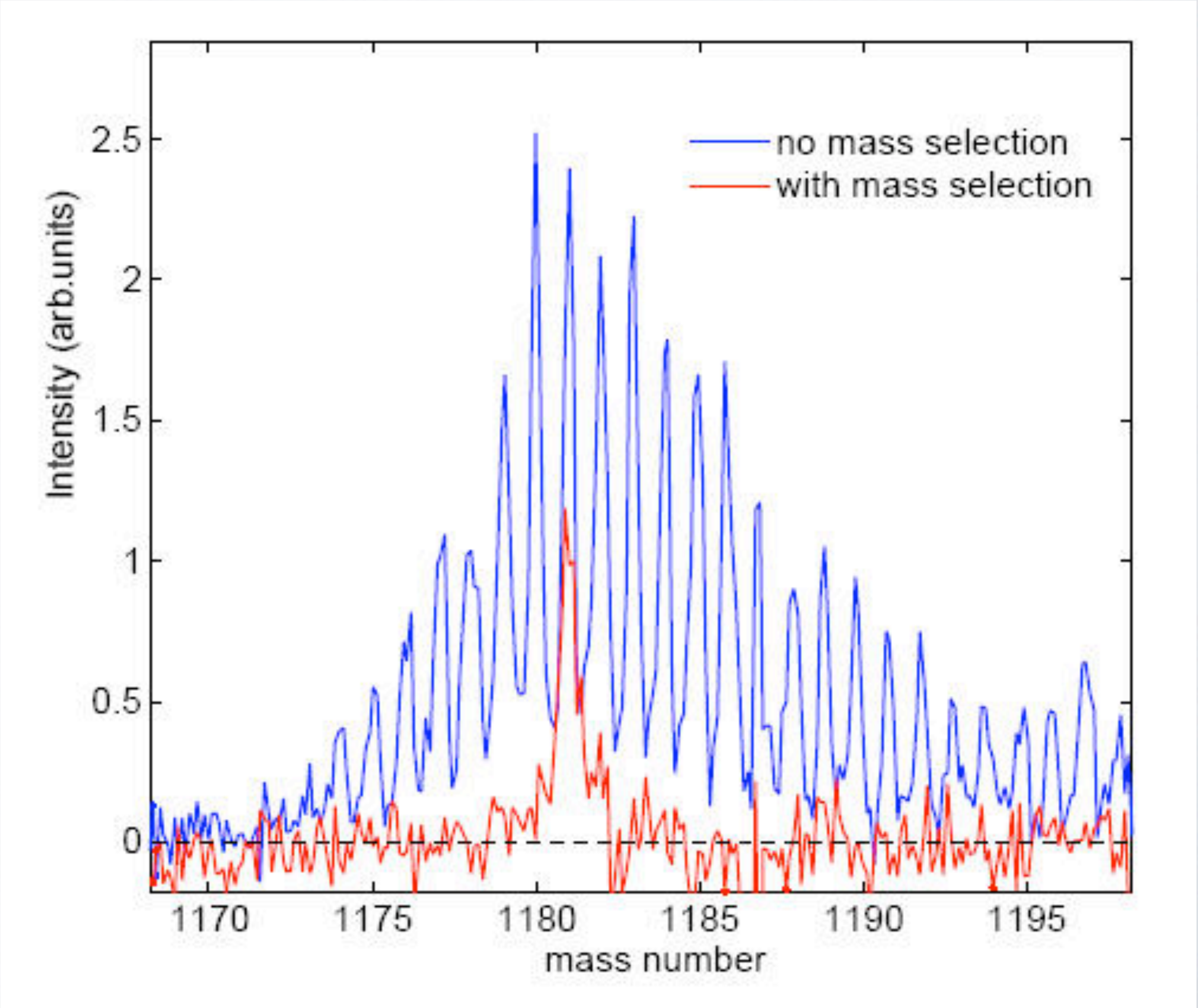
F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)

So what is it good for? (2)

Mass Selection



Apply RF pulse at correct frequency to “kick out” bunches with incorrect oscillation frequency.



So what is it good for? (3)

β decay studies

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu}\right] \left[\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}\right] + \frac{< \vec{J} >}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] \right\}$$

β decay rate

Parameter	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β^+ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

Ion Trap for β decay - been done before (or in planning)

- WITCH - ISOLDE/CERN
- TITAN - TRIUMF
- LPC-Cean - GANIL

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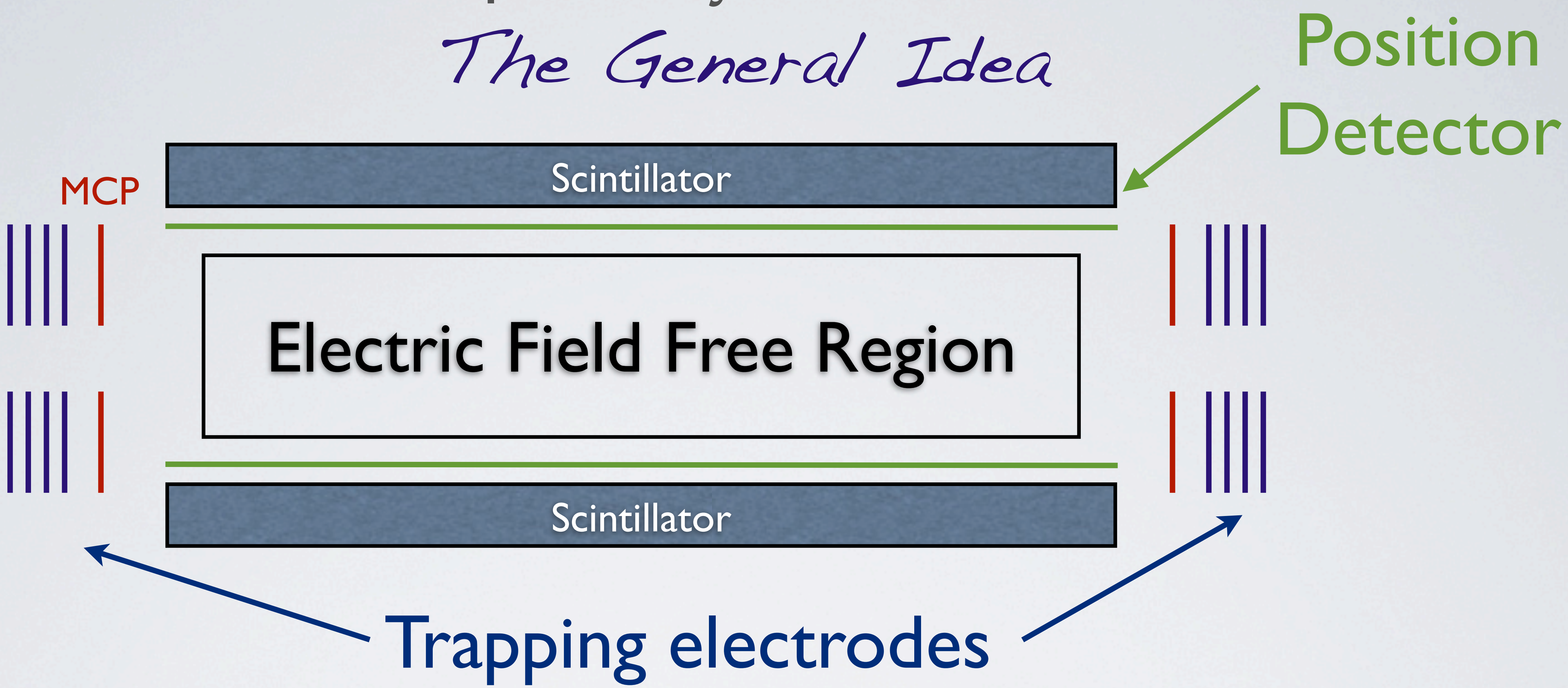
Can we use an EIBT for this?

β-Decay Studies

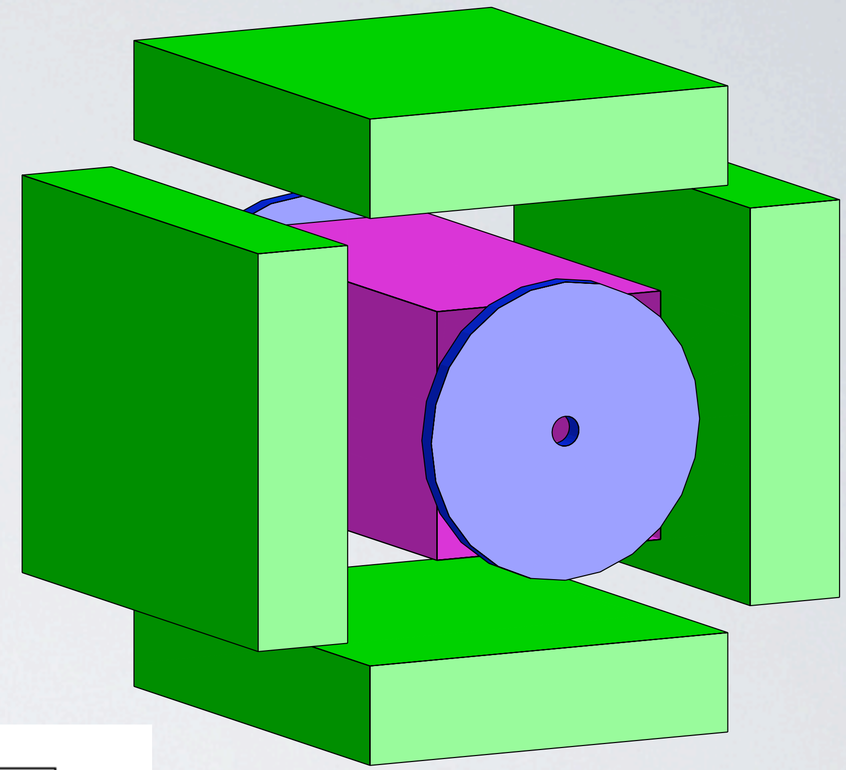
The General Idea

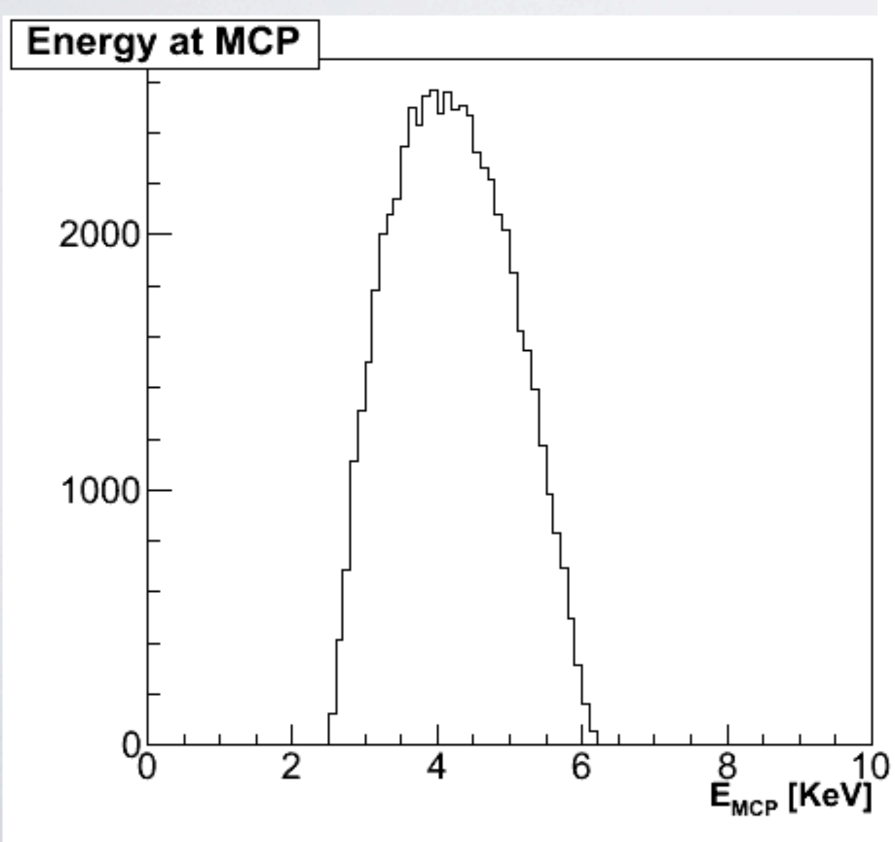


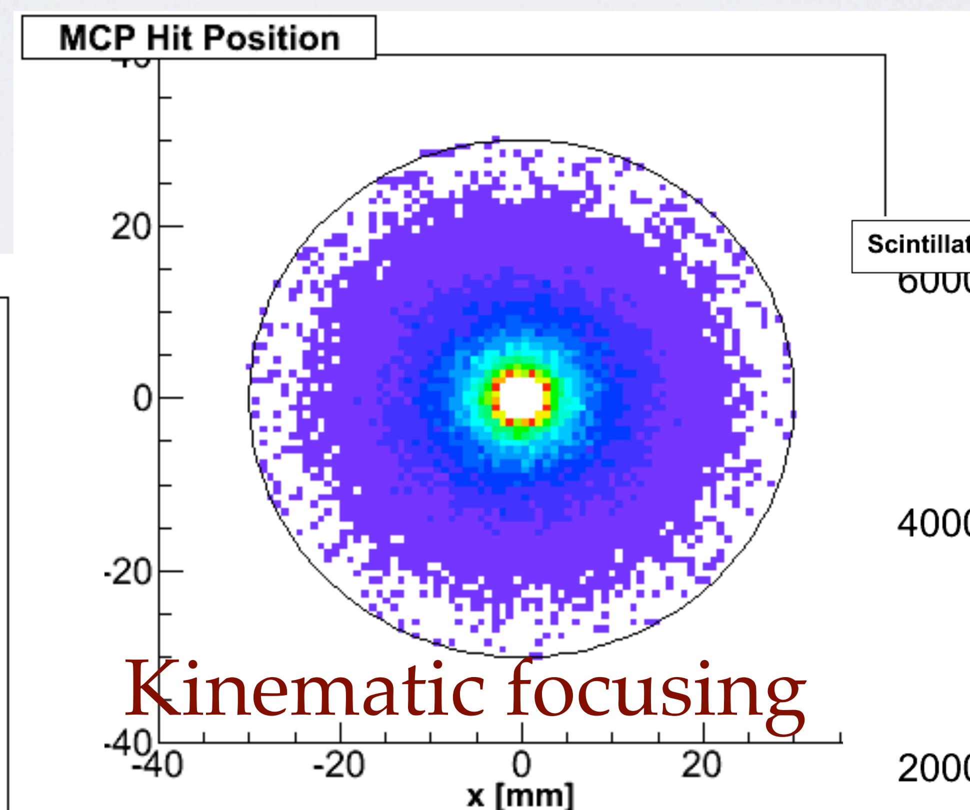
- Recoil ion detected in MCP.
- β detected in position detectors.
- Need bunch position for full reconstruction (multiple scattering of β in detectors).
- Large solid angle + kinematic focussing → detection efficiency > 50%.
- No need for electrostatic acceleration (ions at ~keV). Decay in field free region.

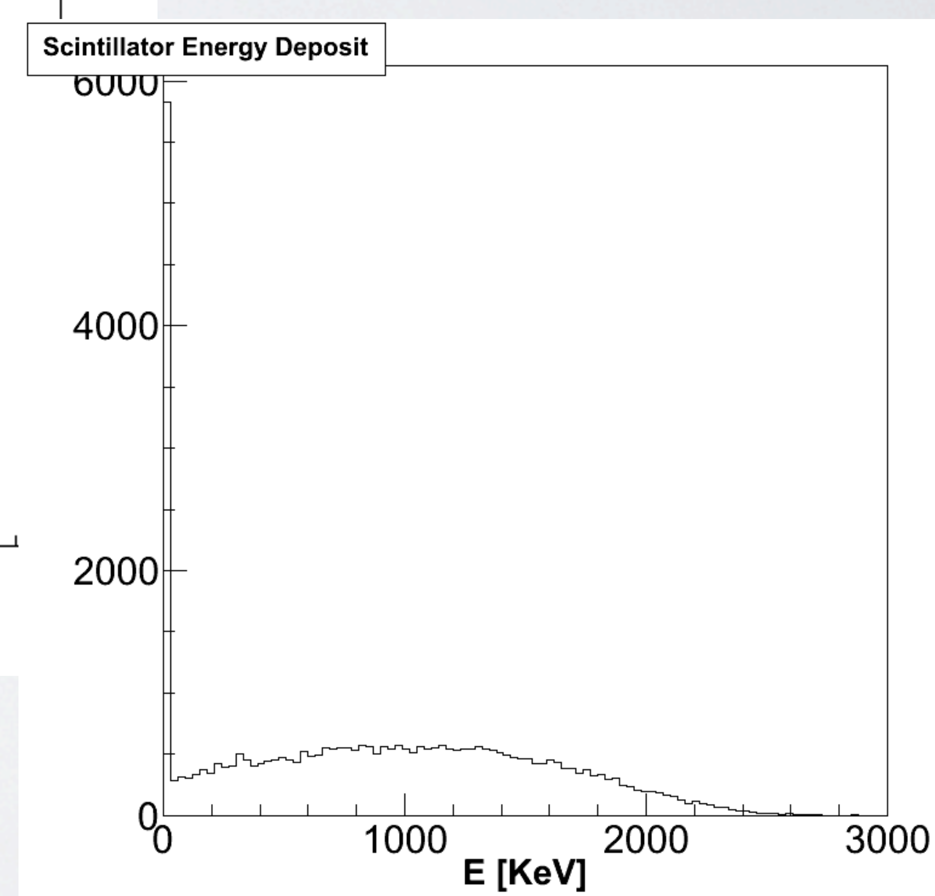
Some Simulation Results

β decay of $^{21}Na^{+} \rightarrow ^{21}Ne^{+} + \beta^{+} + \nu$
Kinetic energy of original ion 4.2KeV
Cuts require hits in only one MCP and only one SSD (no ambiguity)









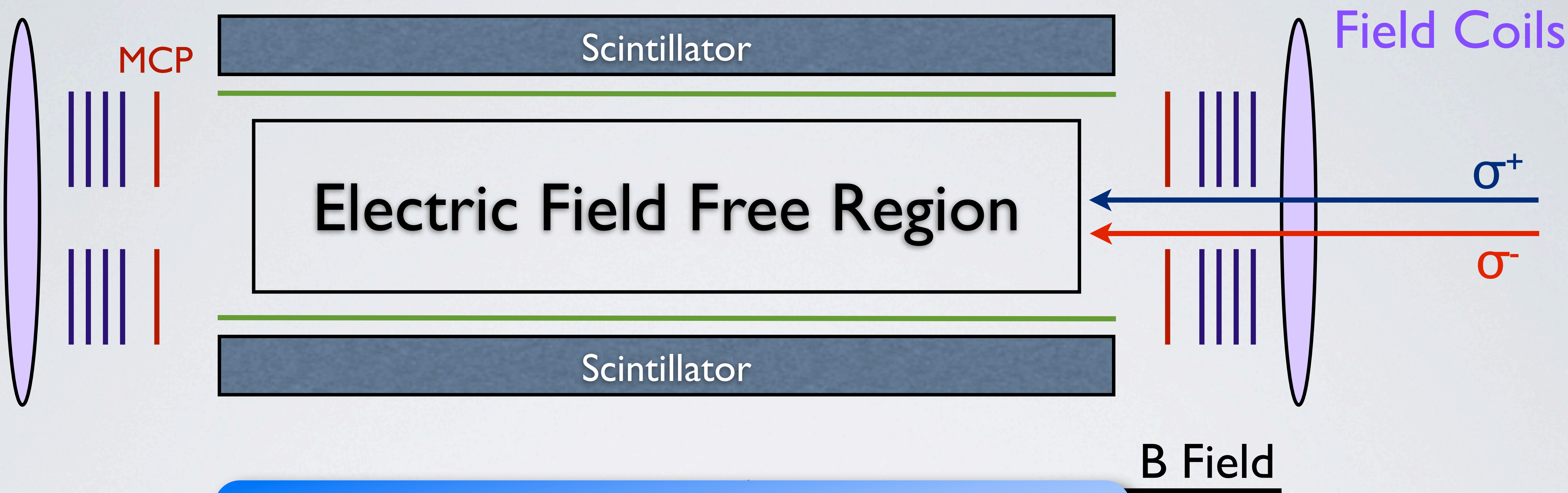
Polarization in β-Decay Studies

Neat trick

- Add on-axis magnetic field for Zeeman splitting.
- On-axis field does not effect the trajectories (V X B = 0).
- Polarize ions with circularly polarized lasers.
- Due to large doppler shift (high energy ions) → two independent ion populations (parallel/anti-parallel).
- MCP hit is determined by direction of ion → each MCP sees only one population.
- Need polarizable ions (usually singly ionized alkaline earth metals - which look like alkali metals when singly ionized).

Polarization in β-Decay Studies

Neat trick



Pretty much only possible in optical and ES traps

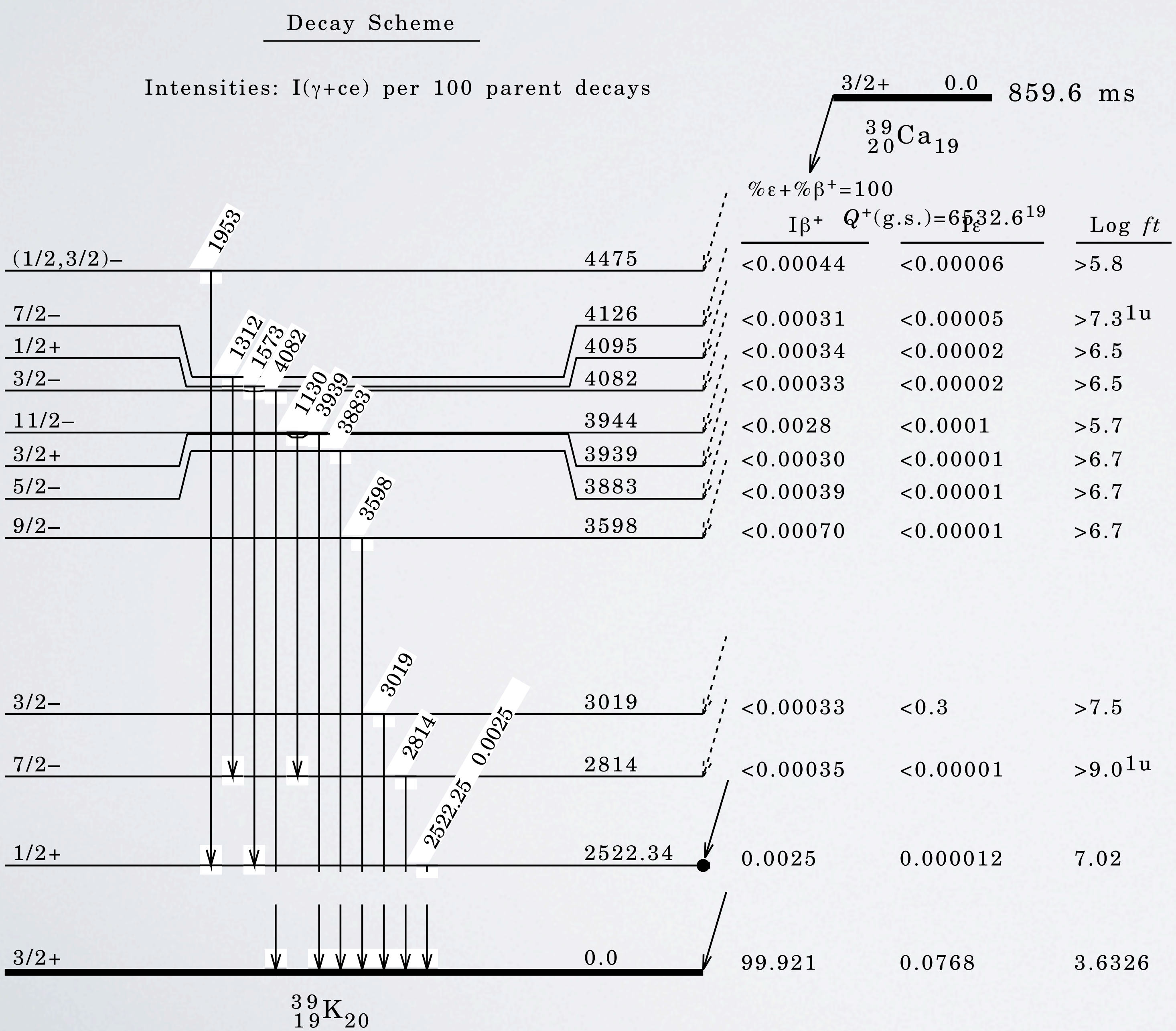
- Add on-axis
- On-axis fiel
- Polarize ion
- Due to large doppler shift (high energy ions) ➞ two independent ion populations (parallel/anti-parallel).
- MCP hit is determined by direction of ion ➞ each MCP sees only one population.
- Need polarizable ions (usually singly ionized alkaline earth metals - which look like alkali metals when singly ionized).

EXAMPLE ^{39}K

?

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + \boxed{a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}} + \boxed{b\frac{m}{E_e}} + c\left[\frac{1}{3} \frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_eE_\nu}\right] \left[\frac{J(J+1)-3<(\vec{J}\cdot\vec{j})^2>}{J(2J-1)}\right] + \frac{<\vec{J}>}{J}\cdot\left[\boxed{A\frac{\vec{p}_e}{E_e}} + \boxed{B\frac{\vec{p}_\nu}{E_\nu}} + \boxed{D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}}\right]\right\}$$

Translates to TOF on MCPs



$^{39}Ca \rightarrow {}^{39}K + \beta^+ + \nu_e$

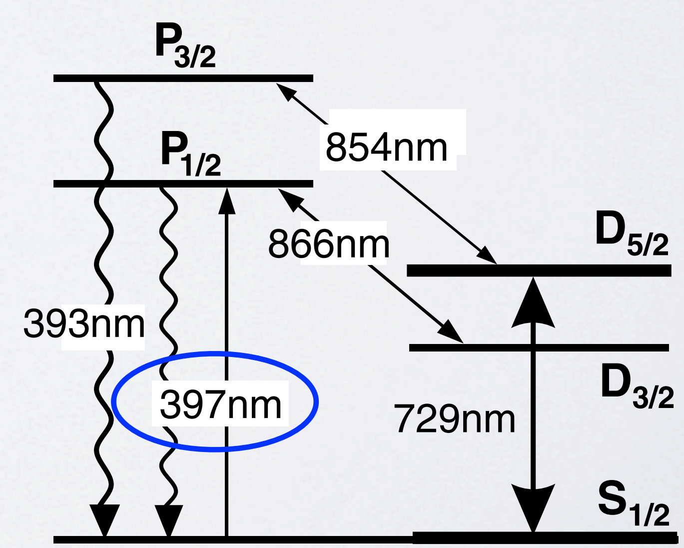
Mirror decay $3/2^+ \rightarrow 3/2^+$

Combination GF and F but calculable

Q = 6.532 MeV

$\tau_{1/2}$=860 ms

For 4.2keV ~360GHz doppler shift ➛ 720GHz σ_+/σ_- separation.



"High Energy" Chemistry (IV)

An experiment looking for a theorist

- Production of radioactive molecules/dimer/clusters is fairly trivial (usually a side effect of the production of radioactive atoms/ions).
- Ionization of such molecules - also trivial.
- ES trap can easily trap molecules of hundreds of amu (also used for bio-molecules).

- Radioactive decay dumps a lot of energy and momentum into the decay products.
- Time scale for decay/emission of shakeoff products is effectively instantaneous.

- Detect molecular decays in ES trap.
- Energy/Momentum sharing between decay products (electronic interaction timescales?).
- Angular correlation in decays (potential?).
- High detection efficiency.
- Mass resolution good enough for selection of different numbers of radioactive atoms in clusters

$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}\,{}^{23}\mathrm{Na}_3}{{}^{4}\mathrm{Na}_{23}} \sim \frac{2}{92}$$

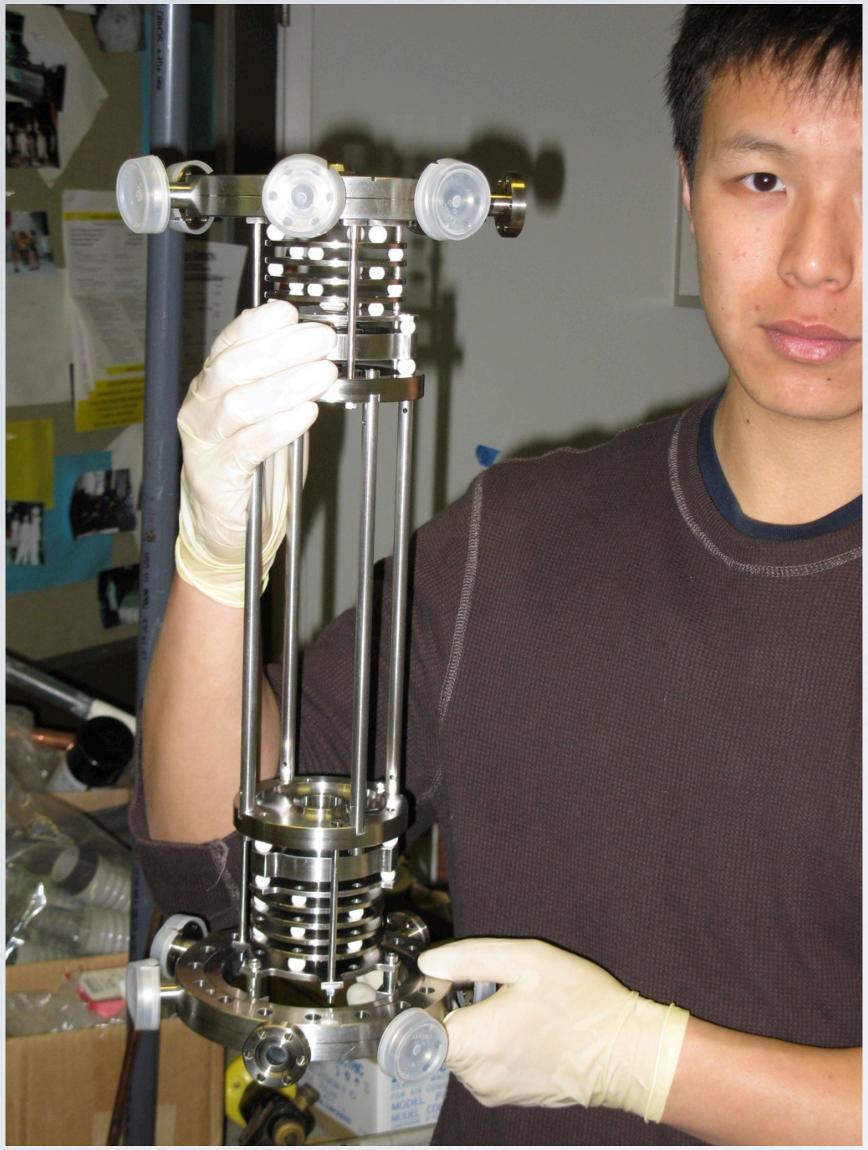
$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}_2\,{}^{23}\mathrm{Na}_2}{{}^{4}\mathrm{Na}_{23}} \sim \frac{4}{92}$$

Trivial

Open Issues

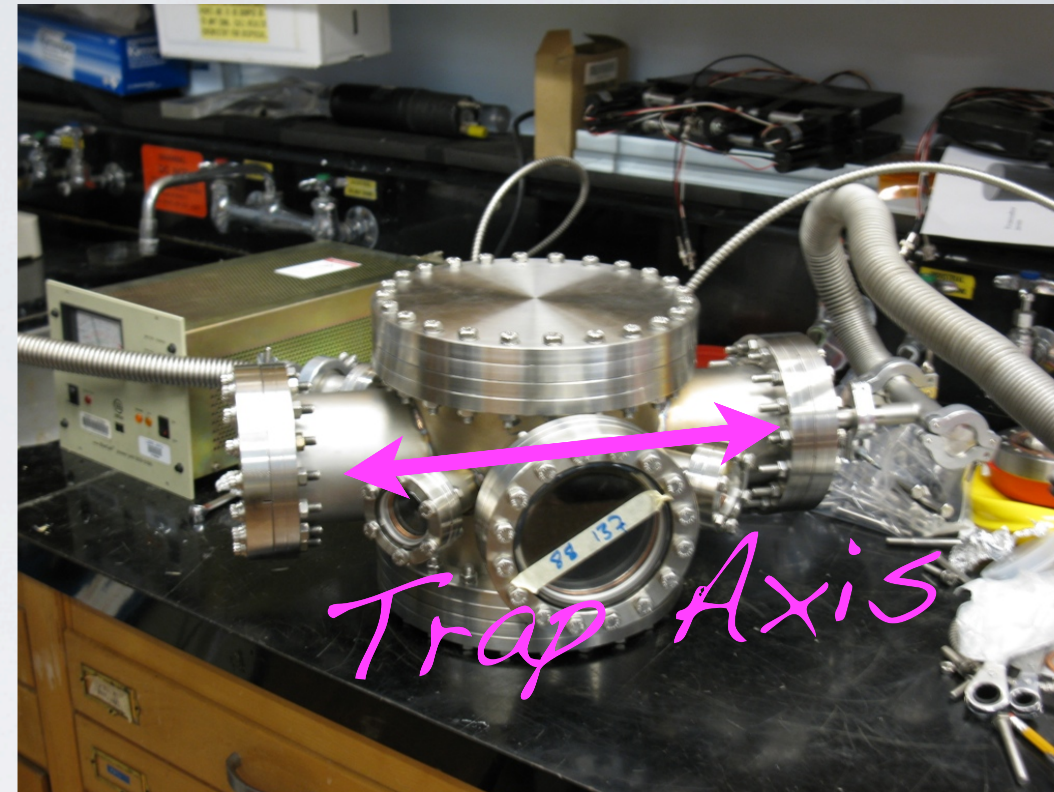
- Installation at LBL (ECR source, isotope selection (*probably start with ^{39}Ar*)) - looking at using ^{14}O beamline.
- Detector design: SSD, Thick GEM+Scintillator .
- Detection:
  - Initially we plan to use image charge detection (but that is relevant for large ion populations or highly charged ions).
  - Single ion detection? (Relevant for SH) *SQUID?*
- Ion bunch size:
  - Injection bunch size (fast switches, but would also be nice to bunch first with say an RFQ).
  - WI are trying to reduce bunch size by RF voltages on the electrodes.
  - We want to try several schemes ("stochastic cooling" - RF kicker, Laser cooling where applicable).

Status



Trap during fit test

Trap electrode sets



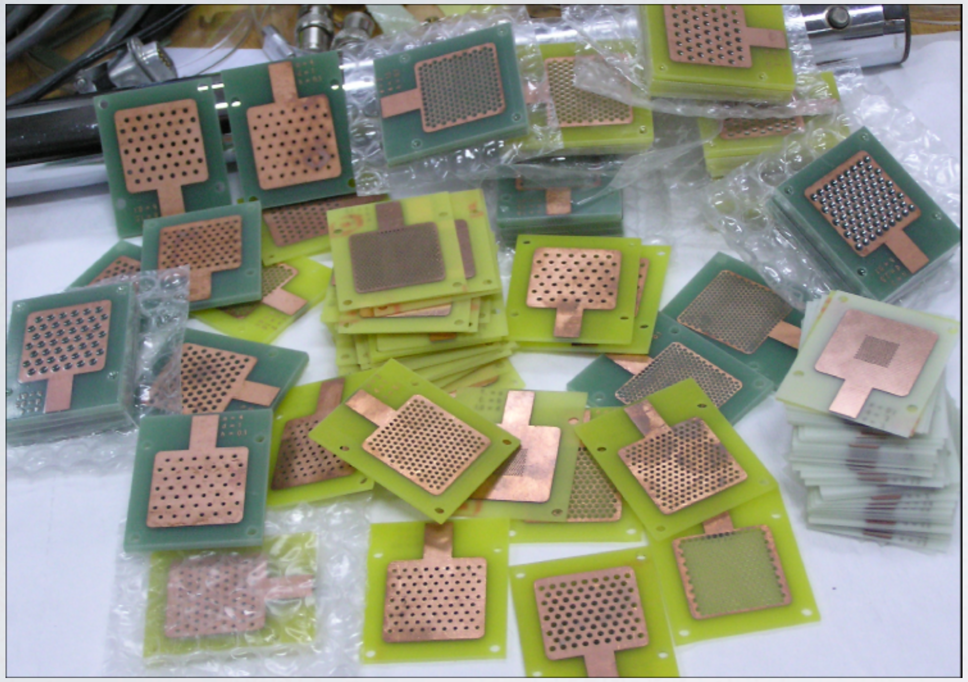
Vacuum Chamber

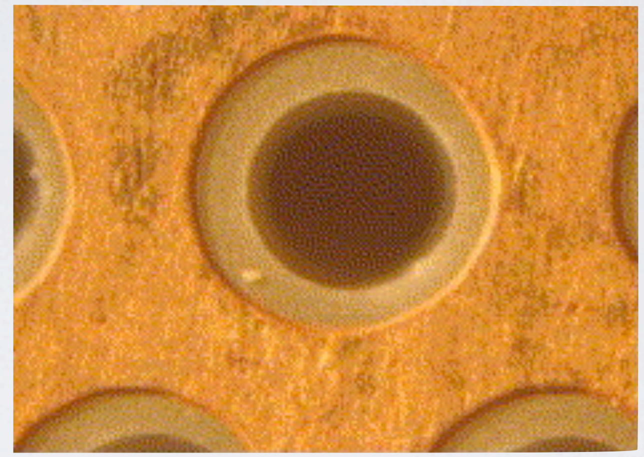
Preliminary Beamline Design

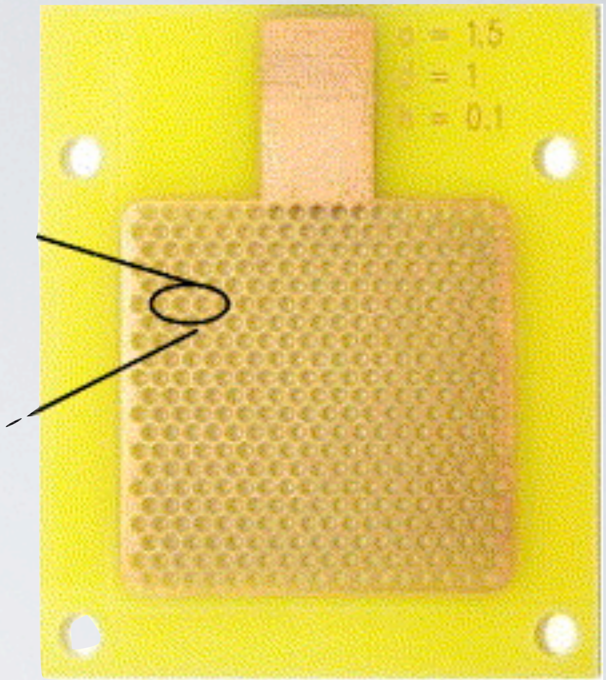
Summary

- Ion traps are useful for many applications.
- But... conventional ion traps are problematic and technically challenging.
- EIBT is an easy and versatile trap to make. Can almost be a "black box" transportable setup.
- We expect to have a trap setup for installation soon, initially for mass spectroscopy but hopefully later for β decay studies.
- Collaboration/Comments/Ideas always welcome.

THGEM - Thick Gaseous Electron Multiplier







Sealed GEM (UV Detector)

M. Balcerzyk et al., IEEE Tran. Nucl. Sci. 50, 1 (2003)